chapter

7

Cellular Respiration

In this chapter

As she skated into the final stretch, speed skater Cindy Klassen dug deep and poured on a final surge of energy to win the women's 1500-m event at the 2006 Winter Olympic Games in Turin. Her winning time of 1 min, 55.27 sec. didn't beat her own world-record time of 1 min, 51.79 sec., which she had set a few months earlier. Klassen won five medals at the games, tying the record for most medals won at an Olympics by a speed skater and breaking the record for most medals won by a Canadian at a single Olympic games.

Klassen's exceptional athletic ability was honed to the elite level through extensive training at Calgary's Olympic Oval. Coaches and exercise physiologists looked at every aspect of Klassen's physical performance and technique, trying to shave seconds off her times. To do this, they had to understand the body's energy demands at the cellular level. Cellular respiration is the process cells use to release energy needed for all kinds of work, including muscle contraction. There are two types of cellular respiration: aerobic respiration and anaerobic respiration. During a race, a speed skater's cells are likely to use both types. In this chapter, you will learn the biochemical steps involved in these processes and how these processes are essential for normal people doing everyday activities, not just for Olympic athletes.

STARTING Points

Answer these questions as best you can with your current knowledge. Then, using the concepts and skills you have learned, you will revise your answers at the end of the chapter.

1. (a) What do organisms do with the oxygen they absorb from the air?
   (b) What is the source of carbon in the carbon dioxide excreted by these organisms?
   (c) Why is carbon dioxide excreted?
2. (a) Why do bakers add yeast to flour and water when making bread?
   (b) When yeast is added to grape juice at room temperature, vigorous bubbling occurs. What gas produces the bubbles?
   (c) After a while, the bubbling stops. Why does it stop?
   (d) What type of beverage is produced by this process?
   (e) What is the name of this process?
3. (a) After a long, hard run, your muscles feel sore and stiff. What is the cause of these symptoms?
   (b) Why do you pant at the end of the run?

Career Connections:
Food Scientist; Kinesiologist

Figure 1
Cindy Klassen started out as a hockey player before taking up speed skating. Both of these activities place great energy demands on the body.

Exploration — Clothespins and Muscle Fatigue

Automobiles and machines must be supplied with gasoline or electricity as a source of energy before they can move. Your muscles require energy in the form of ATP to contract. Muscles can produce ATP by using oxygen (aerobic respiration) or not using it (anaerobic respiration). Anaerobic respiration in muscle cells produces lactic acid. When muscles do a lot of work quickly, lactic acid buildup reduces their ability to contract until exhaustion eventually sets in and contraction stops altogether. This is called muscle fatigue.

Materials: clothespin, timer

- Hold a clothespin in the thumb and index finger of your dominant hand.
- Count the number of times you can open and close the clothespin in a 20 s period while holding your other fingers straight out. Make sure to squeeze quickly and completely to get the maximum number of squeezes for each trial.
- Repeat this process for nine more 20 s periods, recording the result for each trial in a suitable table. Do not rest your fingers between trials.
- Repeat the procedure for the nondominant hand.

(a) Prepare a suitable graph of the data you collected.
(b) What happened to your strength as you progressed through each trial?
(c) Describe how your hand and fingers felt during the end of your trials.
(d) What factors might cause you to get more squeezes (to have less fatigue)?
(e) Were your results different for the dominant and the nondominant hand? Explain why they would be different.
(f) Your muscles would probably recover after 10 min of rest to operate at the original squeeze rate. Explain why.

7.1 The Importance of Cellular Respiration

As you have learned, photosynthesis converts light energy into chemical energy via a series of complex chemical reactions that form a variety of intermediate and final energy-rich molecules. These molecules serve a variety of different energy-related functions within cells.

The primary function of photosynthesis is to convert solar energy into glucose molecules. The glucose molecules may be used immediately. Glucose may then be used immediately, transported to other cells, stored for a medium-term, or used to synthesize molecules that can store energy long-term. Plant cells synthesize starch for long-term storage, by joining many glucose molecules together. Animal and fungal cells link together glucose molecules obtained from their food to form the storage compound glycogen.

When cells require energy for a particular process, it must be supplied in the more directly usable form of ATP. This is the role of cellular respiration. The cells of both animals and plants release the energy stored in the bonds of glucose molecules through the process of cellular respiration. Recall that the process of cellular respiration can be summarized by this equation:

$$\begin{array}{ccccccccccc} \text{glucose} & + & \text{oxygen} & \rightarrow & \text{carbon dioxide} & + & \text{water} & + & \text{energy} \\ C_6H_{12}O_6(s) & + & O_2(g) & \rightarrow & CO_2(g) & + & H_2O(l) & + & \text{energy} \end{array}$$

As we saw with photosynthesis, this equation includes only the compounds at the beginning and end of the process. It is the intermediate products that are used by the cells. In cellular respiration, the intermediate products include NADH, $FADH_2$, and ATP.

NADH an electron carrier, donates electrons in cellular processes

NAD^+ an electron carrier, accepts electrons in cellular processes

$FADH_2$ an electron carrier, donates electrons in cellular processes

FAD^+ an electron carrier, accepts electrons in cellular processes

NADH is the reduced form of **NAD^+** (nicotinamide adenine dinucleotide). **$FADH_2$** is the reduced form of **FAD^+** (flavin adenine dinucleotide). Like NADPH and $NADP^+$ in photosynthesis, these compounds serve as electron carriers. Their role is to transfer electrons through oxidation–reduction reactions. Recall that in an oxidization reaction, electrons are lost and in a reduction reaction, electrons are gained. The transfer of electrons releases energy that can be used in cellular respiration and other cellular processes.

The transfer of electrons from one reactive atom to another produces more stable ions or compounds. The fact that the products have less energy than the reactants indicates that energy is released during the oxidation reaction. This energy can be used to make ATP. **Figure 1** on the next page shows how the energy from an oxidation–reduction reaction is used to attach phosphates to ADP. The product, ATP, is a high-energy compound.

Each time electrons are transferred in oxidation–reduction reactions, energy is made available for the cell to make ATP. Electron transport chains shuttle electrons from one molecule to another. For example, the oxidizing agent NAD^+, along with H^+ remove high-energy electrons from organic molecules and form NADH. It then transfers these electrons to energy releasing chemical pathways. The energy released in these pathways is transferred to ADP and P_i to form ATP.

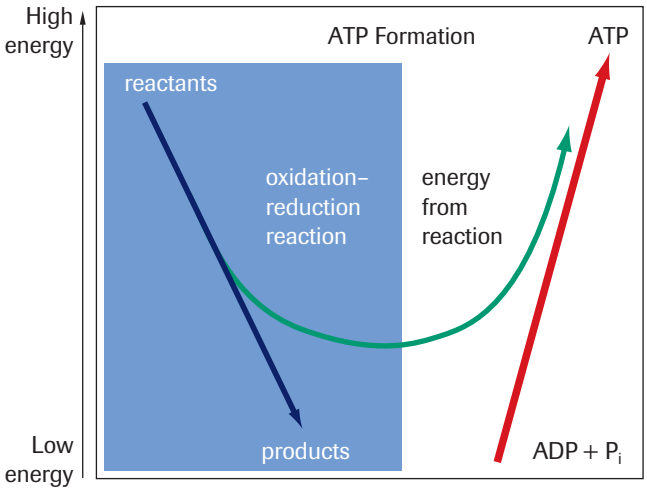

Figure 1
The energy released from the oxidation–reduction reaction is used to attach a free phosphate to ADP to make ATP. Note that ATP is a high-energy compound. The oxidation–reduction reaction could be the transfer of electrons from high-energy compounds such as when NADH is oxidized to form NAD^+ and H^+.

Practice

1. What is the primary function of cellular respiration?
2. How do the oxidation and reduction reactions in electron transfer help to form ATP?

Energy, Cells, and ATP

The energy demands for most cellular processes are supplied by the energy stored in ATP. These energy demands are very diverse. Some, such as chromosome movement in cell division, occur in virtually all living cells, and others, such as bioluminescence (the production of light) occur only in highly specialized cells in a few organisms. These energy demands are not trivial. It is estimated that a typical human cell contains approximately one billion molecules of ATP. These are continuously broken down into ADP and P_i as they release energy to do work, and are then reformed only to be used again.

Active transport (**Figure 2**) can be used to move substances either into or out of the cell. The carrier proteins are often referred to as "pumps." Various types of active transport pumps are found in the membranes of different cells. Potassium and sodium ions are moved into and out of cells by a pump known as the **sodium–potassium pump** (**Figure 3**, next page). Without this pump, nerve cells and muscle cells could not function properly. Other substances, such as vitamins, amino acids, and hydrogen ions are also actively transported across membranes by specialized carrier proteins. All of these pumps require energy from ATP to operate.

active transport the movement of substances through a membrane against a concentration gradient using membrane-bound carrier proteins and energy from ATP

sodium–potassium pump an active-transport mechanism that pumps sodium and potassium ions into and out of a cell

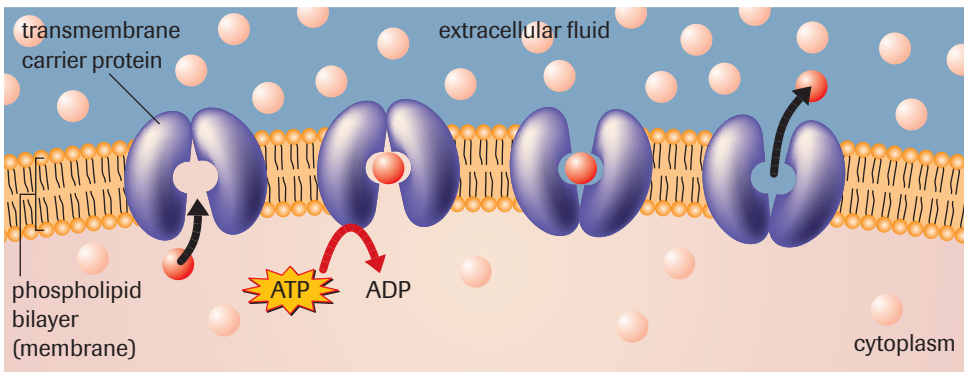

Figure 2
Active transport. The molecule to be transported attaches to an open binding site on one side of the carrier protein. ATP is converted to ADP on the carrier protein and releases energy. The energy causes a change in the shape of the protein that carries the solute to the other side of the membrane.

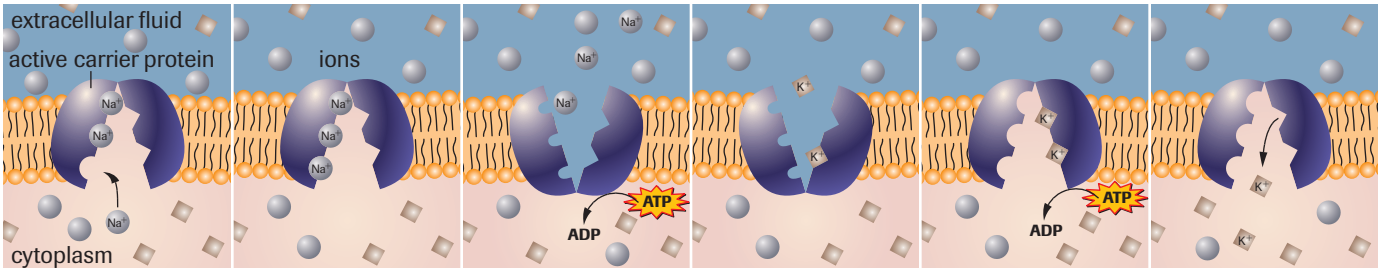

Figure 3
The energy of ATP is used to actively transport three sodium ions out of a cell for every two potassium ions that are transported into the cell.

Another critical use of ATP is that of large-scale motion. In order for you to move, your muscles must contract. The process of muscle contraction involves two different protein molecules sliding past each other. The energy from ATP is used to change the shape of one of the molecules resulting on it pulling on the other. This general process is responsible for all the movements of contractile fibres. (Muscle physiology is covered in detail in Chapter 9.)

Most processes that require ATP energy can be placed in one of categories in **Table 1**.

Table 1 Uses of ATP Energy

Functions requiring ATP	Role of ATP	Examples
motion	• causes various specialized fibres within cells to contract causing movement of the cell or movements within the cell	• chromosome movements during cell division • movement of organelles such as contractile vacuoles emptying • cytoplasmic streaming • formation of pseudopods in lymphocytes or in amoebas • beating of cilia and flagella such as in sperm cells or in certain single-celled organisms
	• causes muscle fibres to contract	• contraction of skeletal, smooth, and cardiac muscles
transport of ions and molecules	• powers active transport of molecules against a concentration gradient across a membrane	• sodium–potassium pump • hydrogen ion pump
building molecules	• provides the energy needed to build many large molecules	• joining amino acids in protein synthesis • Building new strands of DNA during DNA replication
switching reactions on or off	• alters the shape of a molecule, which alters the function of the molecule	• switches certain enzymes on or off
bioluminescence	• reacts with a molecule called luciferin and oxygen	• produces light in some light-generating species such as glow-worms and fireflies

WEB Activity

Simulation—ATP in Action

Follow the Nelson links to view animations of various cellular processes requiring ATP energy. Briefly explain each process and indicate the importance of the process to the organism, and how ATP is involved in the process. You may wish to include a labelled sketch of the process.

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Glucose and ATP

All cells use energy from ATP molecules to meet their metabolic energy needs. However, ATP molecules are not abundant in food and provide a relatively small amount of energy per molecule. Molecules with a higher energy content are therefore useful for both long-term storage of chemical energy and for bulk transporting of chemical energy within cells and multicellular organisms. Carbohydrates, most notably in the form of glucose, are the most usable source of energy. Glucose, along with oxygen, is one of the substrates of cellular respiration. During cellular respiration, some of the energy in glucose is converted to ATP.

A useful analogy for the relationship between ATP, glucose, and other energy-rich molecules is that of money. In our analogy, a cell is like a large factory in which all operations are performed by vending machines that only accept one-dollar coins. In order to perform any task (any cellular action) within the factory, one must insert one or more one-dollar coins into a vending machine. In real cells, the one-dollar coins are analogous to ATP molecules. Virtually all processes conducted by cells use ATP molecules, and only ATP molecules, as their immediate energy source.

In contrast, a glucose molecule contains approximately 100 times as much energy as an individual ATP molecule, but this energy cannot be directly used by the cell. It is like a $100 bill in our cell factory. It is certainly valuable, but must be exchanged for coins before it can be used to operate the vending machines. Similarly, in real cells, the energy content of glucose and other energy-rich molecules can be exchanged or converted into the energy of numerous ATP molecules for the running of cellular activities.

Glucose (**Figure 4**), a simple sugar or monosaccharide, is well suited to its role as a convenient energy supply molecule. Glucose is our "blood sugar." It has a high energy content and is relatively small and highly soluble. These latter two properties make glucose ideal for transportation within and between cells, and throughout the body.

Practice

3. Active transport involves carrier proteins imbedded in the membranes of cells. How do these carrier proteins use ATP to transport molecules across the membrane?
4. How is ATP used in muscle contraction?
5. One glucose molecule has 100 times more stored energy than one ATP molecule. Explain why can't cells use glucose to run their processes.

CAREER CONNECTION

Food Scientist

Food scientists research and develop new and improved methods of food processing, preserving, and packaging. Healthy and safe food products must be continually tested for nutritional value and high quality, so food scientists are essential in food inspection and monitoring programs.

Find out how you might become a food scientist.

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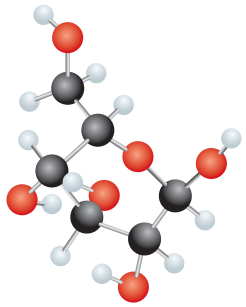

Figure 4
A glucose molecule

Releasing Energy

During respiration, the chemical bonds of reactant food molecules are broken and new bonds are formed in the resulting chemical products. It always takes energy to break chemical bonds, and energy is always released when new bonds form. In simple terms, respiration is an energy-releasing process because more energy is released during the formation of product molecules than is consumed to break apart the reactant molecules (**Figure 5** on page 208).

The energy released by cellular respiration is used to synthesize ATP molecules to be used as the energy currency within the cell. The fundamental role of cellular respiration is to transfer the energy content of food molecules into the energy content of ATP.

Because food molecules such as glucose have a relatively large energy content, a single molecule can be used to form many lower-energy molecules. In our analogy, this is like exchanging the high-energy content of a $100 bill for the energy content of many one-dollar coins. Unlike a simple banking machine, however, the process of cellular respiration is not 100 % efficient. In fact, it is estimated that, at best, only 36 % of the

DID YOU KNOW?

Breaking Chemical Bonds

Energy is only released when new chemical bonds form. Similarly, energy is always required (used) when bonds are broken. In the case of ATP, energy is released when the phosphate group is removed because new bonds form between the phosphate group and other chemicals involved in the reaction. This is the important source of energy available to the cell.

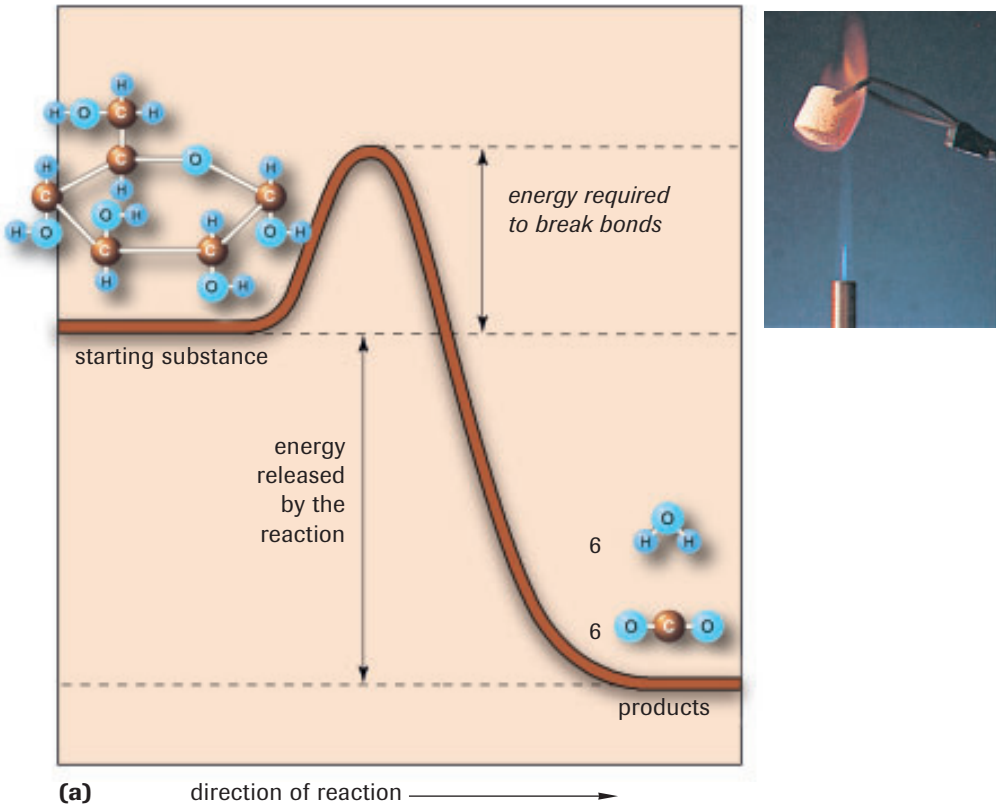

Figure 5
Energy is needed to break the bonds. The energy that is released is the energy from bond formation. The photo shows glucose burning. The high-energy compound, glucose, is converted to low-energy compounds, carbon dioxide, and water.

energy content of a single glucose molecule is converted into the energy of ATP; the remaining 64 % is released as heat. This is analogous to receiving $36 in one-dollar coins in exchange for a $100 bill.

An efficiency of 36 % may not seem very impressive, but keep in mind that cellular respiration involves many complex chemical pathways within cells. For comparison, high-performance racecar engines are slightly less efficient. In these engines only 30 % to 34 % of the energy from fuel combustion is converted to forward motion. The remaining 66 % to 70 % is lost as waste thermal energy. Typical automobiles driven by the public achieve efficiencies of only 25 % to 30 %.

The thermal energy is not waste for all organisms. While the vast majority of living species do not use this thermal energy, two small but significant groups of organisms use it to maintain a constant body temperature. These are warm-blooded organisms (birds and mammals) a group to which we belong. Your body's warmth is a direct product of the inefficient conversion of food energy to ATP energy.

Two Types of Cellular Respiration

While the goal of respiration is a simple one—the conversion of stored food energy into the usable energy of ATP—the process is not. Like photosynthesis, the chemical pathways of respiration are complex and involve many intermediate stages and molecules. A major variable that influences and limits the available chemical pathways of cellular respiration is the presence or absence of oxygen gas.

aerobic cellular respiration the set of reactions that takes place in the cell in the presence of oxygen and releases energy stored in glucose

Aerobic cellular respiration takes place in the presence of oxygen and involves the complete oxidation of glucose. The end products of aerobic cellular respiration are carbon dioxide gas, water, and 36 ATP molecules. Aerobic cellular respiration involves four stages.

Stage 1: glycolysis
Stage 2: pyruvate oxidation
Stage 3: the Krebs cycle
Stage 4: the electron transport chain and chemiosmosis

This equation summarizes aerobic respiration:

$$C_6H_{12}O_6 + 6\,O_2 + 36\,ADP + 36\,P_i \rightarrow 6\,CO_2 + 6\,H_2O + 36\,ATP$$

glucose + oxygen + ADP + inorganic phosphate → carbon dioxide + water + ATP

Anaerobic cellular respiration takes place in the absence of oxygen, and glucose is not completely oxidized. There are two main types of anaerobic cellular respiration, which have different end-products. Both types of cellular respiration occur in two stages that take place in the cytoplasm of the cell.

anaerobic cellular respiration the set of reactions that takes place in the cell in the absence of oxygen and releases energy stored in glucose

Stage 1: glycolysis
Stage 2: fermentation

The equations below summarize the two types of anaerobic cellular respiration that occur in eukaryotes:

$$C_6H_{12}O_6 + 2\,ADP + 2\,P_i \rightarrow 2\,C_2H_5OH + 2\,CO_2 + 2\,ATP$$

glucose + ADP + inorganic phosphate → ethanol + carbon dioxide + ATP

$$C_6H_{12}O_6 + 2\,ADP + 2\,P_i \rightarrow 2\,C_3H_6O_3 + 2\,ATP$$

glucose + ADP + inorganic phosphate → lactic acid + ATP

Notice that the first stage for both aerobic and anaerobic respiration is glycolysis! Also, from the three summary equations, you can see that aerobic respiration produces many more ATP molecules than do either type of anaerobic respiration. You will find out more about these processes in the rest of the chapter.

EXTENSION

Where Pathways Start and Finish

View this brief animation comparing anaerobic and aerobic respiration. Where does each process occur in the cell, and how much ATP does each process produce?

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SUMMARY The Importance of Cellular Respiration

- Cells cannot use high-energy molecules, such as glucose, directly. Cellular respiration converts glucose into energy-containing molecules the cells can use directly, such as ATP.
- Cells use ATP for their immediate energy needs.
- Aerobic cellular respiration takes place in the presence of oxygen and produces 36 ATP molecules per glucose molecule.
- Anaerobic respiration takes place in the absence of oxygen and produces 2 ATP molecules per glucose molecule.

Section 7.1 Questions

1. What are the characteristics of glucose that make it well suited as an energy supply molecule within our bodies?
2. The conversion of glucose energy to ATP energy is less than 50 % efficient. In what way do birds and mammals take advantage of this inefficiency?
3. Briefly describe one cellular process that involves the use of active transport. How is ATP involved in this process?
4. Why is cellular respiration necessary?
5. What are the four stages of aerobic respiration?

7.2 Glycolysis

glycolysis a process for harnessing energy in which a glucose molecule is broken into two pyruvate molecules in the cytoplasm of a cell

In the previous section, you found out that cells may undergo two types of cellular respiration, depending on whether oxygen is available. Aerobic cellular respiration takes place in the presence of oxygen, and anaerobic cellular respiration takes place in the absence of oxygen. However, both types of cellular respiration begin with exactly the same process, called **glycolysis**.

Recall that glucose is a high-energy molecule that cannot be used directly by the cell. Glycolysis is Greek for "sugar splitting," and this accurately describes what happens to glucose during this first stage of cellular respiration. The carbon backbone of glucose is essentially split in half. As you can see in **Figure 1**, glucose is a six-carbon sugar. At the end of glycolysis, glucose has been converted to a three-carbon sugar called pyruvate.

Although it occurs in both types of cellular respiration, glycolysis itself is an anaerobic process: it does not require oxygen. Glycolysis takes place in the cytoplasm of the cell. There are ten reactions in glycolysis, each of which is catalyzed by a specific enzyme in the cytoplasm. During these reactions, two ATP molecules are used and four ATP molecules are produced. Glycolysis therefore produces a net total of two ATP molecules. Glycolysis also produces two $NADH^+$ ions.

EXTENSION

Glycolysis

In this animation, you can see all the intermediate molecules that form as glycolysis converts one glucose molecule to two pyruvate molecules, and how ATP and $NADH^+$ are formed.

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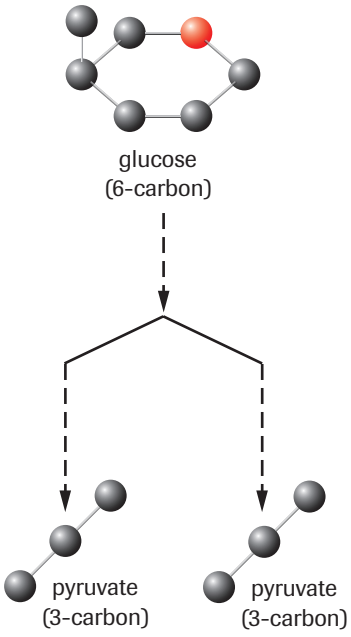

Figure 1
In a series of reactions called glycolysis, a 6-carbon glucose molecule is split into two 3-carbon pyruvate molecules. (For simplicity, the side-group oxygen and hydrogen atoms are not illustrated here.)

Figure 2 on the next page summarizes the reactions of the glycolytic pathway. The long arrow represents the entire pathway of chemical steps that occur during glycolysis. The emphasis is on the key features of this process; the numerous intermediate chemical compounds and reactions are not shown in detail.

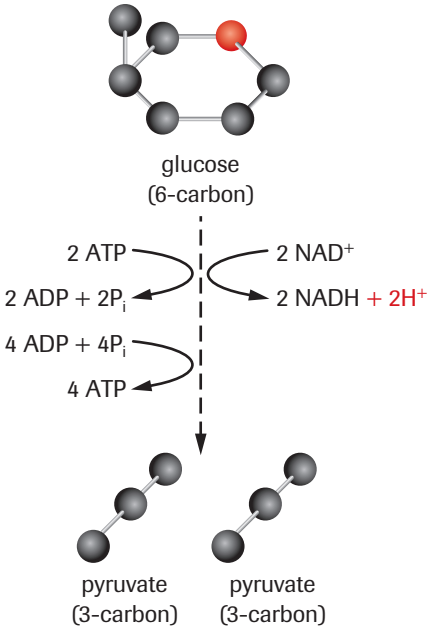

Figure 2
Summary of the glycolytic pathway. Glycolysis is a series of ten chemical reactions, the details of which are not shown.

As you study **Figure 2**, note the following key events:

- Two ATP molecules are used in the first stages of glycolysis. This represents an "investment of energy."
- During glycolysis, oxidation–reduction reactions occur in which two positively charged NAD^+ ions remove hydrogen atoms from the pathway to form two NADH molecules and release two H^+ ions into the cytoplasm.
- In the later stages of glycolysis, enough energy is released to join four ADP molecules with four P_i molecules to form four ATP molecules.
- When glycolysis is complete, the cell has consumed a single glucose molecule and produced two ATP molecules, two NADH molecules, and two pyruvate molecules.
- These ATP molecules are available to supply energy for cellular functions.

Note that the original glucose molecule contained 24 atoms (six C, twelve H, and six O). Of these, six carbon, eight hydrogen, and six oxygen atoms are now held in the two pyruvate molecules ($C_3H_4O_3$). The remaining four high-energy hydrogen atoms are in the form of two NADH molecules and two H^+ ions. **Table 1** lists the reactants and products of glycolysis.

Table 1 The Reactants and Products of Glycolysis

Reactants	Products
glucose	2 pyruvate
2 NAD^+	2 NADH
2 ATP	2 ADP
4 ADP	4 ATP

The net equation for glycolysis is

$$1 \text{ glucose} + 2 \text{ ADP} + 2 P_i + 2 NAD^+ \rightarrow 2 \text{ pyruvate} + 2 \text{ ATP} + 2 \text{ NADH} + 2H^+$$

EXTENSION

ATP and Glycolysis

Listen to this Audio Clip to find out why ATP must be a reactant in glycolysis, even though the role of this process is to produce energy for a cell.

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By itself, glycolysis is not a highly efficient energy-harnessing mechanism. One glucose molecule contains over 90 times as much available energy as a cell obtains when it uses a single ATP. This means that the process of glycolysis transfers only about 2.2 % of the free energy available in glucose to ATP. Some of the energy is released as thermal energy during the process, but the vast majority is still trapped in the two pyruvate and two NADH molecules. The 2.2 % conversion efficiency value applies to glycolysis only; it does not take into consideration the possibility of obtaining additional ATP by further processing pyruvate and NADH in the remaining stages of aerobic respiration.

Some simple single-celled microorganisms can use glycolysis for all their energy needs. However, glycolysis yields only two ATP molecules from each glucose molecule processed. This is not enough to satisfy the energy needs of most multicellular organisms. Nevertheless, all organisms, large and small, multicellular or not, carry out glycolysis either as their only source of ATP or as the first part of a more productive energy-yielding process, such as aerobic respiration.

WWW WEB Activity

Simulation—Respiration in Motion

Respiration involves many reactions and processes that can be difficult to visualize. In this activity, you will explore some animations and act out a specific step for the rest of the class. In groups, follow the Nelson Web links and view various animations of respiration pathways. Your group will then be assigned a specific step or process and will create a short skit. As each group acts out a skit for the class, students will guess which step of respiration is being modelled. Your teacher will provide you with suggestions and rules.

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SUMMARY Glycolysis

- Glycolysis occurs in the cytoplasm. It produces two 3-carbon pyruvate molecules from a 6-carbon glucose molecule. Glycolysis produces two ATP (net) and two NADH.
- The efficiency of glycolysis is only 2.2 % with most of the original energy of the glucose remaining in the pyruvate and NADH molecules.
- The net equation for glycolysis is

  $1\ \text{glucose} + 2\ \text{ADP} + 2\ P_i + 2\ NAD^+ \rightarrow 2\ \text{pyruvate} + 2\ \text{ATP} + 2\ \text{NADH} + 2H^+$

Section 7.2 Questions

1. Write an overall chemical equation for glycolysis.
2. (a) What does *glycolysis* mean?
   (b) List the final products of glycolysis.
3. As a result of glycolysis, only a small portion of the energy of glucose has been converted to ATP. In what form is the rest of the usable energy found at this stage of the process?

Aerobic Cellular Respiration 7.3

Under aerobic conditions (oxygen gas is available), cells will undergo aerobic cellular respiration. The end products of aerobic cellular respiration are carbon dioxide gas, water, and relatively large numbers of ATP molecules. Recall that aerobic cellular respiration has four stages. These are:

Stage 1: glycolysis—a ten-step process occurring in the cytoplasm

Stage 2: pyruvate oxidation—a one-step process occurring in mitochondria

Stage 3: the Krebs cycle—an eight-step cyclical process occurring in mitochondria

Stage 4: the electron transport chain and chemiosmosis (oxidative phosphorylation)—a multi-step process occurring in the inner mitochondrial membrane

In the previous section, you looked at Stage 1, glycolysis, which takes place in the cytoplasm. In this section, you will learn about the last three stages, which all take place within mitochondria.

CHEMISTRY CONNECTION

Combustion of Glucose

Aerobic respiration can be thought of as complete combustion, since the products are carbon dioxide, water, and energy. Your chemistry textbook has more information on combustion reactions.

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INVESTIGATION 7.1 *Introduction*

Measuring Oxygen Consumption in Germinating Seeds

Plant seeds contain living embryos that require energy to carry out the functions of life. When they germinate, they experience high rates of growth and cell division. What happens to a plant seed's rate of energy metabolism when it germinates and starts to grow? Do germinating seeds absorb or release thermal energy?

To perform this investigation, turn to page 229.

Report Checklist

○ Purpose	○ Design	● Analysis
○ Problem	○ Materials	● Evaluation
○ Hypothesis	○ Procedure	● Synthesis
● Prediction	● Evidence	

Investigation 7.1 provides you with an opportunity to conduct controlled experiments on the relationship between growth and the rate of metabolic activity.

Mitochondria

Mitochondria (singular: mitochondrion) are round or sausage-shaped organelles that are usually scattered throughout a cell's cytoplasm. These vital organelles specialize in the production of large quantities of ATP, the main energy-carrying molecule in living cells. The processes that produce ATP in mitochondria cannot proceed without free oxygen.

mitochondrion a eukaryotic cell organelle in which aerobic cellular respiration occurs

Mitochondria possess a double membrane composed of a smooth outer membrane and a highly folded inner membrane (**Figure 1**, next page). The outer membrane plays a role similar to that of the cell membrane, but the inner membrane performs many functions associated with cellular respiration. The inner membrane also creates two compartments within the mitochondrion. The **mitochondrial matrix** is a protein-rich liquid that fills the innermost space of a mitochondrion, and a fluid-filled **intermembrane space** lies between the inner and outer membrane. Each of these compartments play a critical role in aerobic respiration.

mitochondrial matrix the fluid that fills the interior space of the mitochondrion

intermembrane space the fluid-filled space between the inner and outer mitochondrial membranes

Figure 2 on the next page illustrates the four stages of respiration and indicates their locations within the cell.

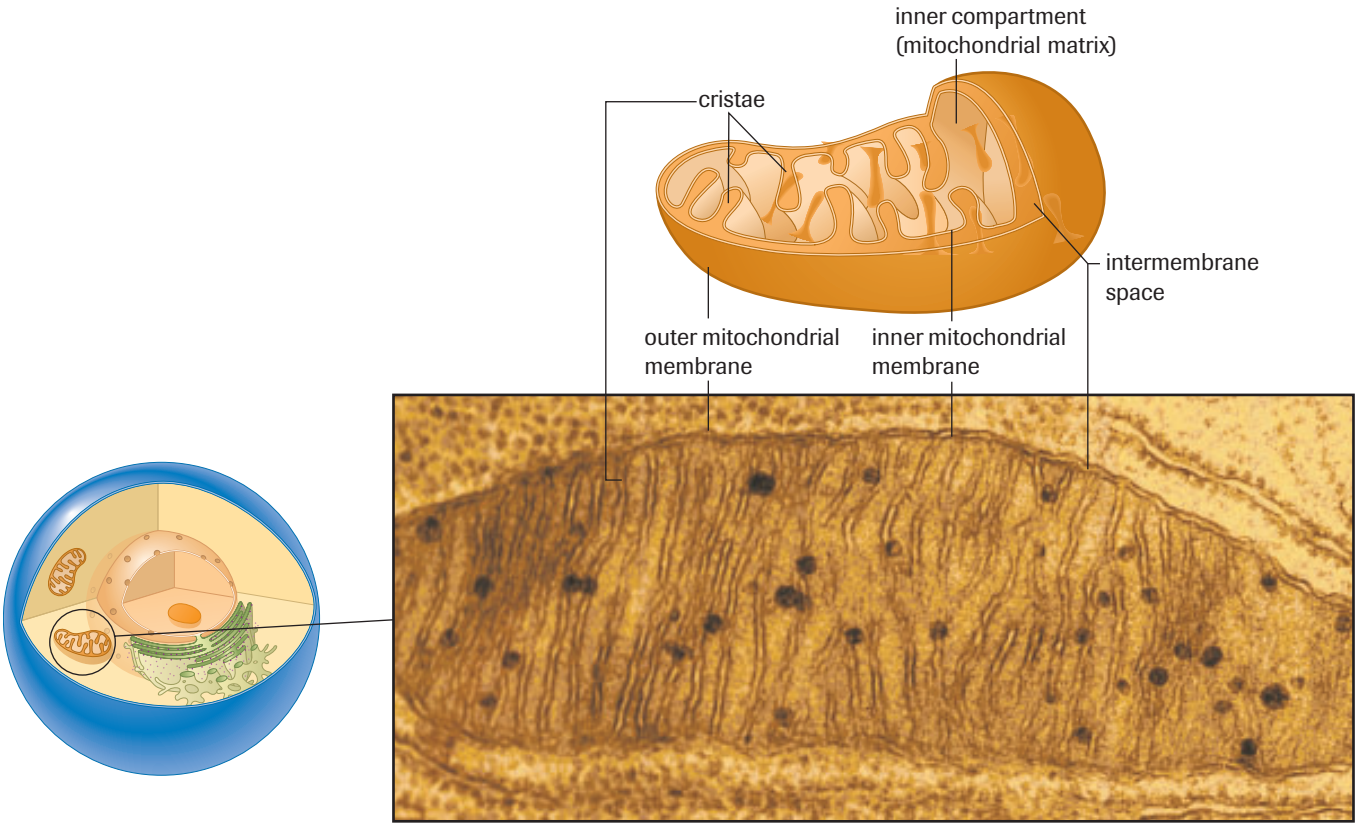

Figure 1
Diagram and transmission electron micrograph of a typical mitochondrion

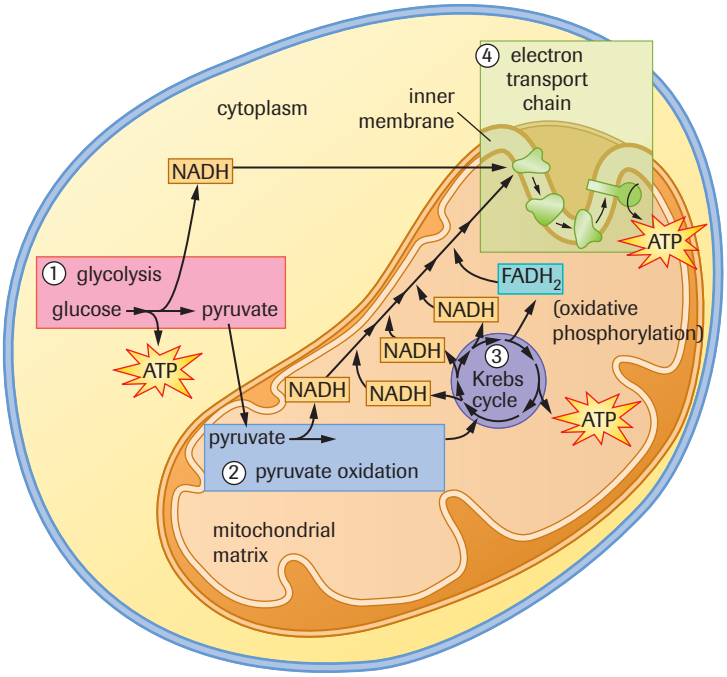

Figure 2
In eukaryotic cells, glycolysis (1) occurs in the cytoplasm (pink). Pyruvate oxidation (2) and the Krebs cycle (3) occur in the mitochondrial matrix (blue and purple respectively). The electron transport chain (4) is embedded in the inner mitochondrial membrane (green).

Stage 2: Pyruvate Oxidation

Recall that by the end of Stage 1, glycolysis, the cell had formed two ATPs, two NADHs and two pyruvate molecules—all in the cytoplasm. Pyruvate oxidation is a chemical pathway that connects glycolysis in the cytoplasm with the Krebs cycle in the mitochondrial matrix (**Figure 2**, previous page). Stage 2 begins when the two pyruvate molecules formed in glycolysis are transported through the two mitochondrial membranes into the matrix. There, the following three changes occur (**Figure 3**):

1. A CO_2 is removed from each pyruvate and released as a waste product. This step is the source of one-third of the carbon dioxide that you breathe out.
2. The remaining 2-carbon portions are oxidized by NAD^+. Each NAD^+ molecule gains two hydrogen ions (two protons and two electrons) from pyruvate, and the remaining 2-carbon compound becomes an acetic acid (acetyl) group. This converts pyruvate to an acetic acid group and transfers high-energy hydrogens to NAD^+.
3. A compound called coenzyme A (CoA) becomes attached to the acetic acid group, forming acetyl-CoA. The acetyl-CoA then enters the next stage of aerobic cellular respiration, the Krebs cycle.

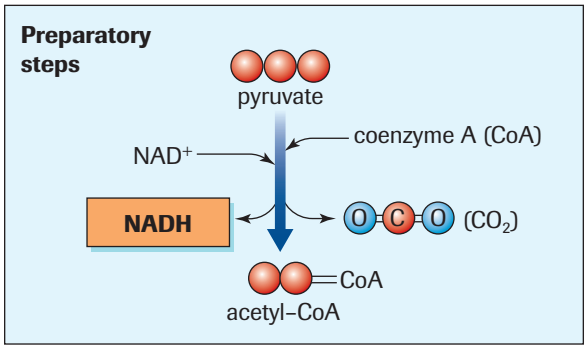

Figure 3
Pyruvate oxidation results in three changes to pyruvate:
1. A CO_2 portion is removed.
2. NAD^+ is reduced by two H atoms.
3. Coenzyme A is attached to the remaining 2-carbon portion (acetyl group).

The two molecules of acetyl-CoA enter the Krebs cycle, while the two molecules of NADH proceed to Stage 4 (electron transport and chemiosmosis). The two CO_2 molecules produced during pyruvate oxidation diffuse out of the mitochondrion and then out of the cell as a low-energy waste product.

Practice

1. What stages of aerobic cellular respiration take place in the mitochondria?
2. What happens to NAD^+ in Stage 2 of aerobic cellular respiration?
3. What is the role of coenzyme A?

Stage 3: The Krebs Cycle

In 1937, Sir Hans Krebs (1900–81), a biochemist working at the University of Sheffield in England, discovered the series of metabolic reactions that became known as the Krebs cycle. He received the 1953 Nobel Prize in Physiology or Medicine for this important discovery. Fritz Albert Lipmann (1899–1986) shared the Nobel Prize with Krebs for his discovery of coenzyme A and the key role it plays in metabolism.

The **Krebs cycle** is an eight-step process, each step catalyzed by a specific enzyme. It is a cyclic process because one of the products of Step 8, is a reactant in Step 1 (**Figure 4**, next page). Key features of the Krebs cycle are outlined in **Table 1**, on the next page.

Krebs cycle a cyclic series of reactions that transfers energy from organic molecules to ATP, NADH, and $FADH_2$, and removes carbon atoms as CO_2

EXTENSION

The Krebs Cycle—Details

In this animation, view the details of the intermediate stages of pyruvate oxidation and the Krebs Cycle. These reactions all take place in the inner compartment of mitochondria.

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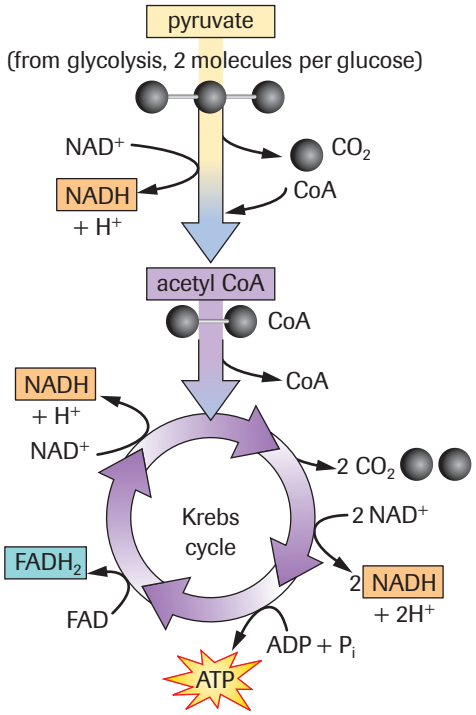

Figure 4

The Krebs cycle begins when acetyl-CoA condenses with oxaloacetate to form citrate. In one turn of the cycle, the two carbon atoms that were originally in a glucose molecule are removed as CO_2, and free energy is transferred to ATP, NADH, and $FADH_2$.

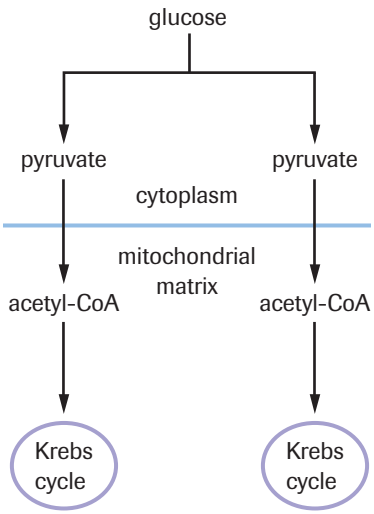

Figure 5

Table 1 Key Features of the Krebs Cycle

• Since two molecules of acetyl-CoA are formed from one molecule of glucose, the Krebs cycle occurs twice for each molecule of glucose processed (**Figure 5**).
• As acetyl-CoA enters the cycle the CoA is released and can be used for the next pyruvate.
• During one complete cycle a total of three NAD^+s and one FAD are reduced to form three NADHs and one $FADH_2$.
• During one complete cycle an ADP and a P_i are combined to form one ATP.
• During one complete cycle two CO_2 molecules are produced. These are released as waste.

Notice that by the end of the Krebs cycle, all six carbon atoms of glucose have been oxidized to CO_2 and released from the cell as metabolic waste. All that is left of the original glucose molecule is some of its free energy in the form of ATP and high-energy NADH and $FADH_2$. NADH and $FADH_2$ now go on to Stage 4 of the process, electron transport and chemiosmosis, where much of their energy will be transferred to ATP.

Stage 4: Electron Transport and Chemiosmosis

NADH and $FADH_2$ eventually transfer the hydrogen atom electrons they carry to a series of compounds, mainly proteins, which are associated with the inner mitochondrial membrane called the electron transport chain (ETC). **Figure 6** on the next page illustrates this process beginning with a single NADH molecule. The NADH gives up two high-energy electrons at the beginning of the ETC. At the same time, it releases an additional

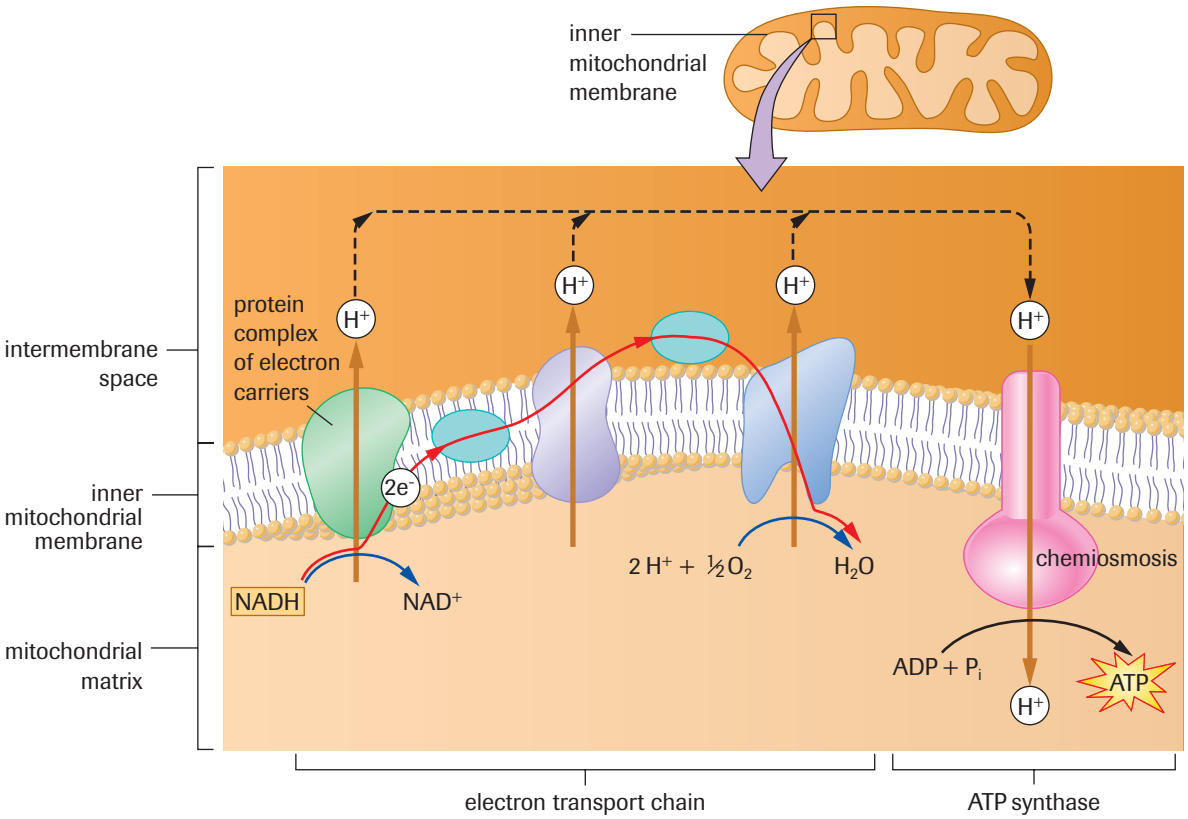

Figure 6
The NADH carries the electrons gained from food to the electron transport chain. As these electrons are passed along carrier molecules, the energy released is used to pump hydrogen ions across the membrane. The electrons are finally accepted by oxygen molecules. Water is the byproduct of the electron transport chain.

H^+ ion into the matrix. The electrons shuttle through the ETC like a baton handed from runner to runner in a relay race. As the electrons move from carrier molecule to carrier molecule in the ETC, they release energy. This energy is used to force a number of H^+ ions from within the mitochondrial matrix across the inner membrane. Each of these ions gains potential energy as they move through proton pumps into the intermembrane space. By the time the two electrons reach the last component of the ETC, they are in a low energy state, having transferred much of their initial energy to the H^+ ions that have been pumped across the inner mitochondrial membrane at three different locations. Oxygen strips the two electrons from the final carrier in the chain and, together with two H^+ ions from the matrix, forms water. As such, oxygen acts as the final electron acceptor in the electron transport process. This final step in the ETC is the reason all aerobic organisms, like humans, must obtain oxygen gas from their environment on a continuous basis.

Note that the ETC is an ongoing process with countless NADHs delivering their electrons to the chain in a continuous flow. $FADH_2$ behaves in a very similar fashion to NADH, delivering its electrons to the ETC. A significant difference however, is that the electrons removed from the $FADH_2$ have a lower energy content and enter the ETC at a different location. The result is that the energy they release is not able to pump as many H^+ ions across the inner mitochondrial membrane.

The electron transport process releases a relatively large quantity of energy. As mentioned earlier, the energy lost by the electron pair during electron transport is used to pump H^+ ions into the intermembrane space. This mechanism converts one form of energy into another—the chemical energy of the electrons is converted to electrochemical potential

DID YOU KNOW ?

Cyanide Blocks the Electron Transport Chain

Cyanide prevents oxygen from acting as the final electron acceptor in the electron transport chain. This disruption virtually shuts down ATP production, resulting in coma and death. That is why cyanide is a poison. However, it is not poisonous to all organisms. Some anaerobic bacteria actually live on cyanide—they use it in the same way aerobes use oxygen!

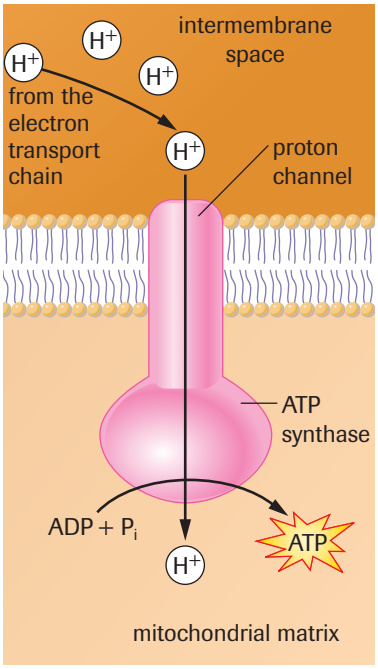

Figure 7
One molecule of ATP is synthesized from ADP and P_i as an H^+ ion passes through the ATPase complex into the mitochondrial matrix from the H^+ reservoir in the intermembrane space.

energy of an H^+ ion gradient that forms across the inner mitochondrial membrane. Electrochemical potential energy is the type of stored energy possessed by a charged battery. It is caused by an accumulation of charged objects (ions, protons, electrons, etc.) on one side of an insulator. As you are about to learn, this energy is used by cells in a process called chemiosmosis to generate large numbers of ATP!

Chemiosmosis and Oxidative ATP Synthesis

The production of ATP within mitochondria is very similar to the ATP synthesis that occurs across the thylakoid membranes in chloroplasts. The H^+ ions that accumulate in the intermembrane space of the mitochondrion during electron transport create an electrochemical gradient that stores energy. This gradient is caused by a higher positive charge in the intermembrane space than in the matrix. The intermembrane space essentially becomes an H^+ reservoir because the inner mitochondrial membrane is virtually impermeable to H^+ ions. The electrochemical gradient creates a potential difference (voltage) across the inner mitochondrial membrane similar to that in a chemical cell or battery. Unable to diffuse through the membrane, the protons are forced to pass through special proton channels associated with the enzyme ATP synthase (ATPase). The energy stored in the electrochemical gradient produces a force that moves H^+ ions through an ATPase complex. As H^+ ions move through the ATPase complex, the energy that is released drives the synthesis of ATP from ADP and inorganic phosphate (P_i) in the matrix (**Figure 7**).

Thus, some of the energy in the pumping of H^+ ions across the membrane is harvested as chemical potential energy in ATP. The electrons removed from a single NADH pump enough H^+ ions across the inner membrane to generate three ATPs, while the electrons from a single $FADH_2$ pump enough H^+ ions across the membrane to yield two ATPs.

Electron transport followed by chemiosmosis is the last stage of the oxidative phosphorylation process that began with the reduction of NAD^+ and FAD with hydrogen atoms from the original glucose molecule. The continual production of ATP by this method is dependent on the establishment and maintenance of an H^+ reservoir. This condition requires the continual movement of electrons through the ETC, which, in turn, is dependent on the availability of oxygen to act as the final electron acceptor. Oxygen is needed to keep the electrons flowing through the ETC. Electrons are "pulled down" the chain in an energy-yielding "fall," similar to gravity pulling a skydiver down toward Earth's surface. The energy released in the fall keeps H^+ ions moving into the H^+ reservoir so that they can "fall back" into the matrix and drive the synthesis of ATP. Since the energy released in the ETC results from a series of oxidation reactions, the end result—the production of ATP—is often referred to as **oxidative ATP synthesis**.

After ATP molecules are formed by chemiosmosis, they are transported through both mitochondrial membranes into the cytoplasm, where they are used to drive processes requiring energy such as movement, active transport, and synthesis reactions throughout the cell.

As you can see, the three stages of aerobic respiration (pyruvate oxidation, the Krebs cycle, and electron transport and chemiosmosis) are all linked to one another and are all dependent on glycolysis for the production of pyruvate. Note that the last stage of the energy transferring processes—chemiosmosis and electron transport—are dependent on the availability of electrons (from food such as glucose) and oxygen (for its ability to act as a final electron acceptor).

DID YOU KNOW ?

Chemiosmosis

Chemiosmosis was first worked out by Peter Mitchell in 1961. He received the 1978 Nobel Prize in Chemistry for "his contribution to the understanding of biological energy transfer through the formulation of the chemiosmotic theory." Mitchell called the process chemiosmosis because the energy that drives the synthesis of ATP comes from the "osmosis" of protons through a membrane from one compartment into another.

oxidative ATP synthesis the production of ATP from a series of oxidation reactions

Practice

4. Describe the function of NAD^+ and FAD in aerobic cellular respiration.
5. What are the final products of aerobic cellular respiration?
6. As a result of glycolysis, pyruvate oxidation, and the Krebs cycle, only a small portion of the energy of glucose has been converted to ATP. In what form is the rest of the usable energy found at this stage of the process?

The Aerobic Respiration Energy Balance Sheet

How much energy was transferred from glucose to ATP in the entire aerobic respiration process? We may calculate two values in answer to this question: a theoretical value and an actual value. Although the actual value gives a more realistic total, it too varies according to the type of cell and various environmental conditions. **Figure 8** summarizes the theoretical yield of 36 ATP and its sources. Note that the NADHs produced during glycolysis are not able to generate three ATP each. Instead they transfer their electrons to FADs which are then used in the ETC to produce two ATPs each.

Numerous experiments have demonstrated that under normal conditions cells are not able to achieve this theoretical maximum yield of 36 ATP per glucose. Instead, cells have an actual yield of approximately 30 ATP per glucose molecule. Recall that glycolysis was only 2.2 % efficient. By comparison, even at this reduced level, aerobic respiration is over 32 % efficient! A dramatic improvement and a compelling reason that so many organisms utilize oxygen gas to release energy from their food.

EXTENSION

Effect of Hypothermia (Reduced Body Temperature) on the Respiration Rate of a Ground Squirrel

Many animals have very low metabolic rates during winter months. In this Virtual Biology Lab, you will manipulate the body temperature of a ground squirrel to test how this affects its rate of aerobic cellular respiration.

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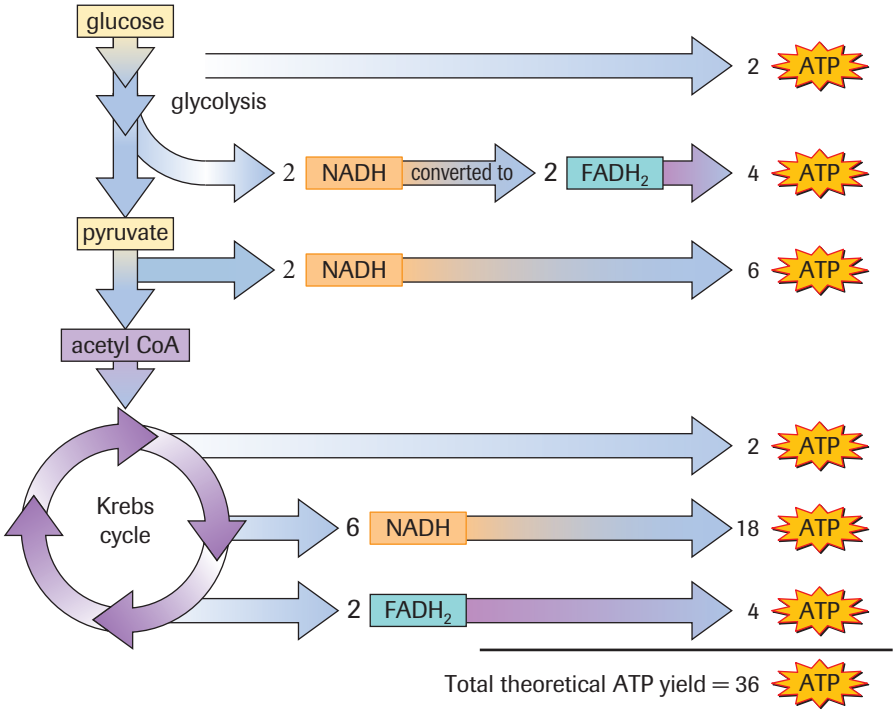

Figure 8
Theoretical ATP yield from the aerobic respiration of one glucose molecule

SUMMARY Aerobic Cellular Respiration

- Aerobic cellular respiration involves four stages: glycolysis, pyruvate oxidation, the Krebs cycle, and electron transport and chemiosmosis.
- Pyruvate oxidation occurs in the mitochondria. In the process, a CO_2 portion is cleaved from pyruvate and removed from the cell as waste. The remaining 2-carbon acetyl group attaches to coenzyme A to produce acetyl-CoA. In this reaction, two NADH and two CO_2 are formed (one for each of the two pyruvate molecules).
- The Krebs cycle occurs in the mitochondrial matrix. The two carbon atoms introduced by acetyl-CoA are removed as two CO_2. One ATP, one $FADH_2$ and three NADH are produced.
- The electron transport chain, associated with the inner mitochondrial membrane, transports electrons through a series of reactions that transfers energy to H^+ ions as they are pumped into the mitochondrial intermembrane space. This creates an electrochemical gradient.
- In chemiosmosis, protons move through ATPase complexes embedded in the inner mitochondrial membrane, releasing free energy that drives the synthesis of ATP.
- Oxygen is the final acceptor of electrons that pass through the electron transport chain. If oxygen is not available, the Krebs cycle, electron transport, and chemiosmosis come to a halt.
- The overall equation for aerobic respiration is:

$$\text{glucose } (C_6H_{12}O_6) + 6\ O_2 + 36\ ADP + 36\ P_i \rightarrow 6\ CO_2 + 6\ H_2O + 36\ ATP$$

Section 7.3 Questions

1. Arrange the following types of cells in order of increasing number of mitochondria in the cytoplasm: nerve cell, skin cell, fat cell, heart muscle cell. Provide a rationale for your sequence.
2. (a) In eukaryotic cells, where does glycolysis occur?
   (b) What two products of glycolysis may be transported into mitochondria for further processing?
3. Describe two functions that mitochondrial membranes serve in energy metabolism.
4. Why is aerobic cellular respiration a more efficient energy-extracting process than glycolysis alone?
5. (a) What part of a glucose molecule provides electrons in cellular respiration?
   (b) Describe how electron transport complexes set up a proton gradient in response to electron flow.
   (c) How is the energy used to drive the synthesis of ATP?
   (d) What is the name of this process?
   (e) Who discovered this mechanism?
6. (a) Distinguish between an electron carrier and a terminal electron acceptor.
   (b) What is the final electron acceptor in aerobic respiration?
7. Explain how the following overall equation for cellular respiration is misleading:

$$C_6H_{12}O_6 + 6\ O_2 \longrightarrow 6\ CO_2 + 6\ H_2O$$

8. Explain why CO_2 does not serve as a source of free energy in living systems.
9. (a) Explain the role of $FADH_2$ in the electron transport chain.
   (b) Explain why $FADH_2$ does not generate as many ATP molecules as NADH does.
10. Aerobic cellular respiration stops if no oxygen is present. Explain why.

Anaerobic Cellular Respiration 7.4

Glycolysis allows organisms to obtain energy from nutrients in the absence of oxygen. As you will recall, during glycolysis NAD^+ is converted to NADH. Glycolysis cannot occur without this reaction. Cells possess a limited supply of NAD^+ and, without a mechanism to convert NADH into NAD^+, glycolysis will come to a halt. If glycolysis stops, ATP can no longer be formed and cell death soon follows.

In aerobic organisms, all NADH is converted into NAD^+ in the ETC—a process that requires oxygen. Without oxygen, the ETC cannot operate and, as a result, anaerobic organisms have evolved several ways of recycling NAD^+ and allowing glycolysis to continue. One method involves transferring the hydrogen atoms of NADH to certain organic molecules instead of to the electron transport chain. This process is called fermentation. Bacteria have evolved dozens of different forms of fermentation, but eukaryotes (organisms whose cells contain nuclei, such as humans) primarily use two methods: **alcohol fermentation** and **lactic acid fermentation**.

Both types of fermentation processes occur in only two stages, all within the cytoplasm of the cell. All fermenting organisms perform the same first stage—glycolysis. It is the second stage that is variable, with different organisms using different pathways.

Stage 1: glycolysis—the identical 10-step process used in aerobic respiration

Stage 2: fermentation—recycles some of the products of glycolysis in two different pathways where either carbon dioxide and ethanol (alcohol fermentation) or lactic acid (lactic acid fermentation) are the final waste products

Alcohol Fermentation

In alcohol fermentation, NADHs molecules produced during glycolysis pass their hydrogen atoms to acetaldehyde, a compound formed when a carbon dioxide molecule is removed from pyruvate by the enzyme pyruvate decarboxylase, as shown in **Figure 1**.

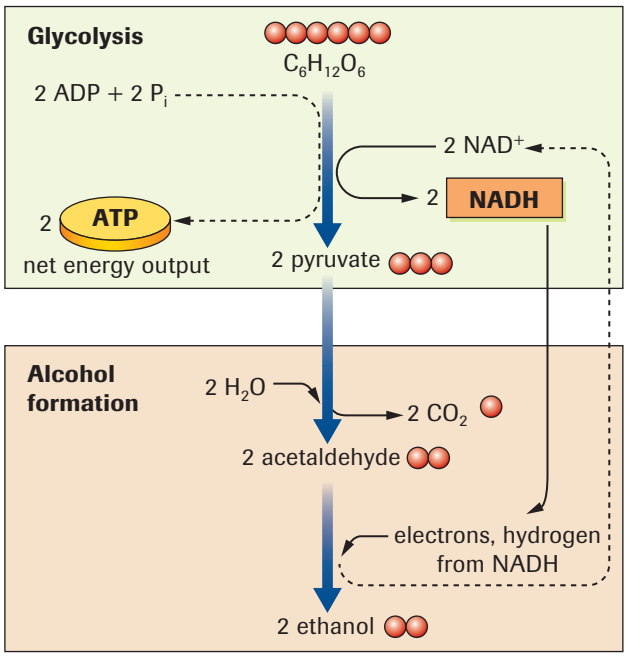

Figure 1
Alcohol fermentation creates ethanol and carbon dioxide from glucose. In the process, NADH is oxidized to NAD^+, allowing glycolysis to continue.

EXTENSION

Effect of Physical Activity on Scorpion Respiration Rate

In this Virtual Biology Lab, you will modify the amount of muscle activity in a scorpion and observe the effect on respiration rate. Will the animal move from aerobic respiration to anaerobic respiration? How would you be able to tell?

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alcohol fermentation a form of fermentation occurring in yeast in which NADH passes its hydrogen atoms to acetaldehyde, generating carbon dioxide, ethanol, and NAD^+

lactic acid fermentation a form of fermentation occurring in animal cells in which NADH transfers its hydrogen atoms to pyruvate, regenerating NAD^+ and lactic acid

Figure 2
Alcohol fermentation is used in the production of baked goods and products such as wine, beer, and soy sauce.

This forms ethanol, the type of alcohol used in alcoholic beverages. This process recycles NAD^+ and so allows glycolysis to continue. The two ATP molecules produced during glycolysis satisfy the organism's energy needs, and the ethanol and carbon dioxide are released as waste products. The overall equation for alcohol fermentation is

$$\text{glucose } (C_6H_{12}O_6) + 2\ \text{ADP} + 2\ P_i \rightarrow 2\ \text{ethanol } (C_2H_5OH) + 2\ CO_2 + 2\ \text{ATP}$$

Applications of Alcohol Fermentation

Humans have learned ways of making use of these products of fermentation. Alcohol fermentation carried out by yeast (a variety of single-celled fungi) is of great historical, economic, and cultural importance. Breads and pastries, wine, beer, liquor, and soy sauce are all produced using fermentation (**Figure 2**).

Bread is leavened by mixing live yeast cells with starches (in flour) and water. The yeast cells ferment the glucose from the starch and release carbon dioxide and ethanol. Small bubbles of carbon dioxide gas cause the bread to rise (or leaven), and the ethanol evaporates away when the bread is baked. In beer making and winemaking, yeast cells ferment the sugars found in carbohydrate-rich fruit juices, such as grape juice. The mixture bubbles as the yeast cells release carbon dioxide gas and ethanol during fermentation. In winemaking, fermentation ends when the concentration of ethanol reaches approximately 12 %. At this point, the yeast cells die as a result of alcohol accumulation and the product is ready to be consumed as a beverage.

Microbial fermentation is used to make many different food products. **Table 1** lists a few of these foods and the raw materials from which they are made.

Table 1 Sample Food Products Dependent on Microbial Fermentation

Food	Raw material
bread	flour
soy sauce	soya bean
vinegar	alcohol (from fruit or grain fermentation)
chocolate	cacao bean
sauerkraut	cabbage
wine and beer	grapes and barley

Figure 3
Although Louis Pasteur (1822–95) is best known for introducing the process of pasteurization, he also pioneered the vaccines against rabies and anthrax.

While such fermentation products have been produced for centuries, it was not until 1803 that scientists discovered that the yeasts being used in many of these processes were alive. Later, Louis Pasteur (**Figure 3**) provided experimental evidence that yeast was responsible for alcohol fermentation. His work on these processes helped lead him to the monumental discovery that many diseases are caused by microbes.

Practice

1. What is the key advantage of anaerobic respiration? Suggest some specific situations in which this would benefit organisms in the natural environment.
2. Name a nonalcoholic final product of alcohol fermentation, other than ATP.
3. (a) How many molecules of ethanol are produced by the fermentation of one molecule of glucose?
   (b) How many molecules of carbon dioxide are produced during the fermentation of one molecule of glucose?
   (c) How much oxygen is used during the fermentation of one glucose molecule?

mini Investigation — Facultative Microbes

Facultative organisms are those organisms that are able to use either aerobic or anaerobic respiration depending on the environmental conditions in which they are living. Yeast is a good example of this type of organism. In the presence of oxygen, they use aerobic respiration to generate their ATP supplies, in the absence of oxygen they use glycolysis and alcohol fermentation. In this mini investigation you will examine the changes in net gas production associated with a switch from aerobic to anaerobic respiration.

Materials: 3 g Brewers yeast, 50 mL grape juice or apple cider (with no preservatives), 125 mL Erlenmeyer flask, large balloon

- Place 3 g of yeast in the Erlenmeyer flask.
- Add 50 mL of grape juice or apple cider to the flask.
- Allow the yeast to sit for several minutes and then gently stir the mixture to disperse the yeast.
- Cover the flask tightly with the balloon
- Make regular observations over a period of several days documenting changes in the apparent gas volume in the balloon.
- At the end of your experiment, remove the balloon and smell the contents of the flask. Record your observations.
- Display your results using a graphical format.

(a) Were the initial conditions aerobic or anaerobic?
(b) The presence of oxygen gas does not prevent or interfere with the chemical reactions in anaerobic respiration and fermentation pathways. Why then does yeast not continue to follow these pathways when oxygen is present?
(c) During aerobic respiration what gas(es) is produced and consumed? How might this influence the volume of gas in the balloon?
(d) During anaerobic respiration what gas(es) is produced and consumed? How might this influence the volume of gas in the balloon?
(e) Was there evidence of a switch from anaerobic to aerobic or aerobic to anaerobic respiration? Account for these results.
(f) What distinctive odour provided evidence of anaerobic respiration or fermentation?
(g) Suggest modifications to the experimental design that could be used to maintain aerobic conditions over an extended period of time.

EXPLORE an issue

Aerobic versus Anaerobic Waste Treatment

Issue Checklist

● Issue	○ Design	● Analysis
● Resolution	● Evidence	● Evaluation

Human activities produce large amounts of organic wastes. Solid, liquid, and gaseous wastes must be treated to prevent contamination of soil, water, and air. Cities generate enormous volumes of human sewage and household waste (**Figure 4**). Industry and agriculture also produce large volumes of organic waste. Many microbes can use a wide range of organic material as food so they are often used to process waste into less harmful or even valuable compounds. Choosing whether to use an anaerobic or an aerobic microbe to process waste is influenced by many factors.

Figure 4
Garbage collection is a familiar activity in most municipalities.

Understanding the Issue
In a group, use print and Internet resources to research the factors influencing the choice of aerobic and anaerobic systems for a number of the following waste/biomass processing systems:

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- biogas generation
- municipal sewage treatment plant
- household/cottage septic systems
- landfill gas production
- biomass ethanol production

For each system investigate and report on the following:

Raw material(s) – Give a general description of their chemical and physical makeup.

Source of raw materials – Where and why is this material produced in large quantities?

Microbial respiration system(s) – Does the processing of this material involve anaerobic, aerobic, or both forms of respiration/fermentation?

Products – What respiration/fermentation products are produced in this process? Of what value are these products?

Evaluation – Based on your research, is the system an effective way to process waste/biomass? What recommendations would you make to improve or enhance efficient use of this system?

Questions

1. How is oxygen provided in waste treatment systems?
2. How does the presence or absence of oxygen influence the rate of sewage waste processing?
3. Compare, in general terms, the energy content of the final products of aerobic versus anaerobic systems. How can this difference influence the choice of systems and the benefits and uses of such systems?
4. Ethanol is now being used widely as a gasoline fuel additive. What is the main source of this ethanol? What are the benefits of adding ethanol to gasoline?

Lactic Acid Fermentation

Under normal conditions, animals such as humans obtain energy from glucose by aerobic respiration. However, during strenuous exercise, muscle cells demand more ATP energy than can be supplied by aerobic respiration alone. Under such conditions additional ATPs are supplied by lactic acid fermentation, shown in **Figure 5**.

EXTENSION

The Impacts of Lactic Acid Production

Listen to this Audio Clip for an explanation about lactic acid production during a workout and how this lactic acid has both positive and negative impacts on the body.

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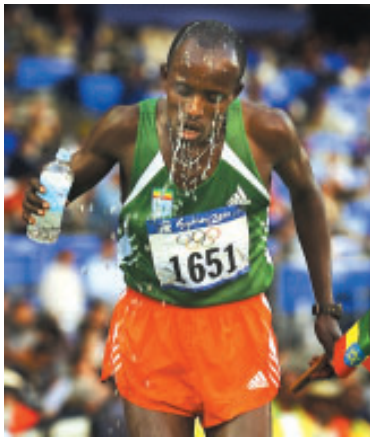

Figure 6
Marathon runners are fatigued after a race because of the accumulation of lactic acid in their muscles. Panting provides the oxygen needed to metabolize the excess lactic acid.

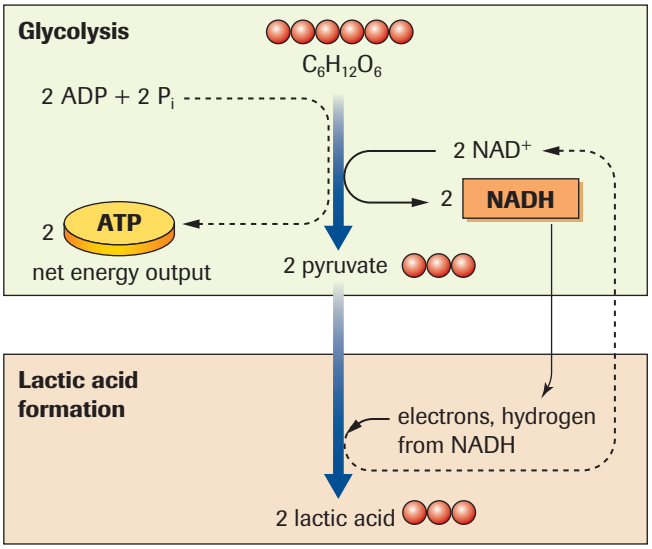

Figure 5
Lactic acid fermentation produces lactic acid from glucose. In the process, NADH is oxidized to NAD^+, allowing glycolysis to continue.

In lactic acid fermentation, NADH produced in glycolysis transfers its hydrogen atoms to pyruvate in the cytoplasm of the cell, regenerating NAD^+ and allowing glycolysis to continue. This results in a change of pyruvate into lactic acid. The overall equation for lactic acid fermentation is

$$\text{glucose } (C_6H_{12}O_6) + 2\ ADP + 2\ P_i \rightarrow 2 \text{ lactic acid } (C_3H_6O_3) + 2\ ATP$$

Accumulation of lactic acid molecules in muscle tissue causes stiffness, soreness, and fatigue. Lactic acid is transported through the bloodstream from the muscles to the liver. When vigorous exercise ceases, lactic acid is converted back to pyruvate, which then goes through the remaining stages of aerobic respiration. The extra oxygen required to chemically process this lactic acid (through the aerobic pathway) is referred to as oxygen

debt. Panting after bouts of strenuous exercise is the body's way of "paying" the oxygen debt (**Figure 6**, previous page).

Exercise Physiology: VO_2 max and the Lactic Acid Threshold

Exercise physiology is a branch of biology that deals with the body's biological responses to exercise. Scientists in this field try to answer such questions as "Why do muscles become sore and fatigued after a bout of strenuous exercise? How can athletes train to control fatigue and maximize the amount of oxygen that enters their bloodstream? Why does exercise deplete the body of its water reserves and how can athletes avoid dehydration?" Exercise physiologists search for solutions to practical problems faced by individuals who engage in sports and athletic activities. The most common problem faced by athletes is a shortage of energy. Therefore, particular emphasis is placed on the study of aerobic and anaerobic metabolism and its relationship to cardiopulmonary fitness, also known as aerobic fitness. Aerobic fitness is a measure of the ability of the heart, lungs, and bloodstream to supply oxygen to the cells of the body (especially the muscle cells) during physical activity. Aerobic fitness is one of the factors used by physiologists to judge a person's overall physical fitness. Other factors include muscular strength, muscular endurance, flexibility, and body composition (the ratio of fat to bone to muscle).

Since muscle cells need energy from ATP to contract, it is assumed that ATP production (by aerobic respiration) will be increased if more oxygen is absorbed and used by the cells of the body (especially muscle cells) in a given period of time. Exercise physiologists measure a value called the **maximum oxygen consumption (VO_2 max)**, as a measure of a body's capacity to generate the energy required for physical activity. VO_2 max measures the maximum volume of oxygen, in millilitres, that the cells of the body can remove from the bloodstream in one minute per kilogram of body mass while the body experiences maximal exertion. VO_2 max values are typically expressed in mL/kg/min, and are measured directly by a maximal exercise test, also known as a treadmill exercise test. During the test, the person or animal is forced to move faster and faster on a treadmill while expired air is collected and measured by a computer (**Figure 7**). The entire test usually lasts between 10 min and 15 min. Needless to say, the test is not pleasant since one must achieve a rather painful state of maximal exertion. Indirect methods of estimating the value of VO_2 max have been developed that require much less physical strain.

In general, individuals with higher VO_2 max values may be considered more aerobically fit than individuals with lower values.

VO_2 max values vary between 20 mL/kg/min and 90 mL/kg/min. The average value for a typical North American is about 35 mL/kg/min, while elite endurance athletes reach values of 70 mL/kg/min. **Figure 8**, on the next page, shows average VO_2 max values for the athletes of various sports. VO_2 max values may be increased with exercise and training, but genetic variation helps to explain why everyone cannot train to be an elite athlete. Exercising harder, more frequently, and for longer durations will increase VO_2 max values to a degree. However, VO_2 max values also decrease with age. In any case, there is not always a direct correlation between VO_2 max values and overall athletic performance. Although it is true that elite athletes have VO_2 max values that are higher than the population mean, factors such as mental attitude, running efficiency, and the amount of lactic acid produced during exercise greatly influence overall performance.

Since oxygen cannot reach all the body's mitochondria all the time, lactic acid fermentation occurs continuously as you exercise. However, as exercise intensity increases, lactic acid production increases. The lactic acid threshold is the value of exercise intensity at which blood lactic acid concentration begins to increase sharply (**Figure 9**, next page). Exercising at or below this intensity may be sustainable for hours, but exercising

EXTENSION

Estimating VO_2 max

In this activity, you will carry out the Rockport Fitness Walking Test. This is a standard test used to estimate the value of VO_2 max. You will walk a distance of 1.6 km on level ground as quickly as possible, without running. You will record how long it took you complete the walk, and measure your heart rate after the walk. You will then substitute these measurements, your age, gender, and mass, into an equation to calculate your VO_2 max.

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maximum oxygen consumption, VO_2 max the maximum volume of oxygen, in millilitres, that the cells of the body can remove from the bloodstream in one minute per kilogram of body mass while the body experiences maximal exertion

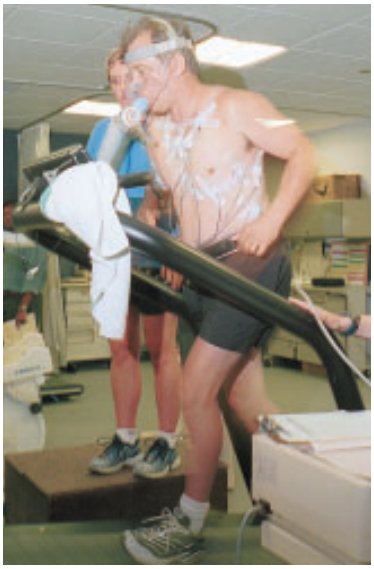

Figure 7
A maximal exertion test being conducted in a human performance lab. The apparatus is used to make precise measurements of VO_2 max.

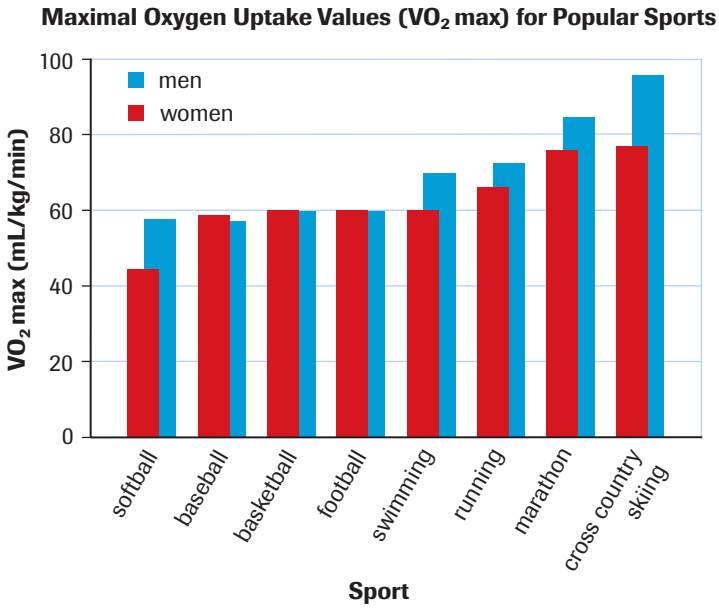

Figure 8
VO_2 max values for athletes in popular sports

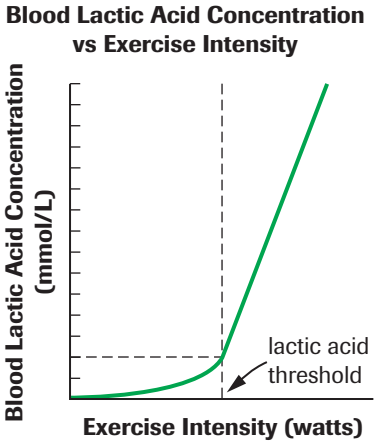

Figure 9
The lactic acid threshold

beyond the lactic acid threshold may limit the duration of the exercise because of increased pain, muscle stiffness, and fatigue.

In general, athletic training improves blood circulation and increases the efficiency of oxygen delivery to the cells of the body. The result is a decrease in lactic acid production at any given exercise intensity level and an increase in the lactic acid threshold. With a higher **lactic acid threshold**, the person will be able to sustain greater exercise intensities and improved athletic performance. One measure of performance is the percentage of VO_2 max at which the lactic acid threshold is reached. Untrained individuals usually reach the lactic acid threshold at about 60 % of VO_2 max. Elite endurance athletes typically reach their lactic acid thresholds at or above 80 % of VO_2 max.

lactic acid threshold the value of exercise intensity at which lactic acid production increases

CAREER CONNECTION

Kinesiologist

Kinesiologists work in the field of human movement, helping people rehabilitate from physical injuries. To be accepted into a kinesiology program, candidates must possess high marks in biology, chemistry, math, and physics. Kinesiologists work in a variety of settings, including hospitals, clinics, and fitness centres. Some large corporations, such as General Motors, hire kinesiologists to advise on ways to improve workers' safety and efficiency on assembly lines—known as ergonomics. Research other career opportunities in the specialized field of ergonomics.

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Practice

4. In addition to ATP, name the other final products of both types of fermentation.
5. How does a human feel the presence of lactic acid in the tissues of the body?
6. Why are VO_2 max values not perfectly correlated with overall athletic performance?

Supplements and Toxins

In addition to our own physical condition and health, environmental factors can have an impact on cellular respiration. Chemicals we ingest or inhale can directly affect cellular respiration pathways in a variety of ways. Some compounds may act as buffers—countering the acidic effects of lactic acid fermentation and potentially enhancing short-term athletic performance. Other chemicals may act as metabolic poisons—inhibiting cellular respiration by interfering with a critical step in a chemical pathway.

Creatine phosphate occurs naturally in the body and in foods. More recently, some high-performance athletes have consumed it as a dietary supplement. Creatine phosphate may serve as a source of energy by donating its phosphate to ADP, thus creating ATP. Some have also hypothesized that increasing the amount of creatine in the diet might increase the concentration of creatine phosphate in muscles. This might increase the availability

of high-energy phosphate for ATP and energy production during muscle contraction. Creatine also has the potential to act as a buffer in muscle cells and potentially counter or delay the onset of some of the symptoms associated with lactic acid fermentation.

Many claims have been made regarding the value of creatine supplements. It is said to enhance athletic performance by increasing muscle strength and mass, by providing an instant energy source, and by delaying fatigue. The ultimate benefits and risks associated with its use are not conclusive, however, and potential harmful side-effects are possible. Many medical researchers urge caution and do not recommend its use.

While some chemicals, like creatine phosphate, may enhance respiration under certain conditions, other chemicals have the potential to do quite the opposite. Chemical toxicity can result from a wide range of mechanisms. As you may know, carbon monoxide poisoning is due to this gas's ability to bind to the hemoglobin proteins in your red blood cells. These proteins are responsible for carrying oxygen gas throughout your body. Carbon monoxide competes aggressively for the same binding sites on the hemoglobin molecules. The result is a severe drop in your blood's oxygen-carrying capacity and possible death by asphyxiation. Oxygen is the final electron acceptor that drives the electron transport chain. Without oxygen there is an immediate halt to electron transport and the pumping of hydrogen ions across the inner mitochondrial membrane. Without this activity, H^+ ions are no longer available to drive the formation of ATP—the cell's vital energy source. Cell death follows shortly thereafter.

Rather than limiting the body's access to one of the reactants in cellular respiration, some toxic compounds such as cyanide and hydrogen sulfide directly act on a specific reaction within a respiration pathway.

DID YOU KNOW ?

Death and Rigor Mortis

There are two things that happen soon after death: one is a gradual drop in body temperature, and the other is stiffening of the muscles, known as rigor mortis. Rigor mortis is caused not by the drop in body temperature, but by the fermentation of glucose in muscle cells, leading to high levels of lactic acid. The lactic acid causes muscle tissue to become rigid. Rigor mortis sets in much sooner if death occurs immediately following strenuous activity, such as running.

mini Investigation Metabolic Poisons

Cyanide and hydrogen sulfide are metabolic poisons that enter the environment both from natural sources and as a direct result of human activities. In this mini investigation you will research and document various aspects of the toxicity, sources, and environmental and human health implications of these compounds. Imagine that you are one member of a research team that is preparing a resource binder on environmental toxins.

Using Internet and print resources provide answers and explanations for each of the following and then present them in the form of a two page Fact Sheet that would be suitable for inclusion in the binder.

(a) What stage(s) in cellular respiration are affected by cyanide and hydrogen sulfide?

(b) With what specific compounds do these poisons interfere?

(c) Do these compounds have any commercial value as toxins? Give examples of their use.

(d) Do these compounds occur naturally? If so, where are they found?

(e) What human activities produce these toxins as an industrial pollutant?

(f) How do these toxins impact the health of the environment in the locations in which they occur?

(g) What methods, if any, are used to reduce cyanide and/or hydrogen sulfide pollution?

SUMMARY Anaerobic Cellular Respiration

- When oxygen is not available, eukaryotes still carry out glycolysis. They recycle the NAD^+ needed for glycolysis by transferring the hydrogen atoms in NADH to pyruvate or acetaldehyde.
- In alcohol fermentation, a molecule of CO_2 is removed from pyruvate, forming a molecule of acetaldehyde. The acetaldehyde is converted to ethanol by attaching hydrogen from NADH.

- In lactic acid fermentation, pyruvate molecules accept the hydrogens from NADHs and form molecules of lactic acid.
- Alcohol fermentation occurs in yeast cells and is used in wine, beer, and bread making.
- Lactic acid fermentation occurs in animal muscle cells during strenuous exercise.
- The maximum oxygen uptake, or VO_2 max, is the maximum volume of oxygen that the cells of the body can remove from the bloodstream in one minute per kilogram of body mass while the body experiences maximal exertion. The lactic acid threshold is the value of exercise intensity at which blood lactic acid concentration begins to increase sharply.
- Chemical toxins, such as carbon monoxide, cyanide, and hydrogen sulfide, can hinder cellular respiration.

Section 7.4 Questions

1. List two differences between aerobic respiration and fermentation.
2. A student regularly runs 3 km each afternoon at a slow, leisurely pace. One day, she runs 1 km as fast as she can. Afterward, she is winded and feels pain in her chest and leg muscles. What is responsible for her symptoms?
3. What role does alcohol fermentation play in the food industry?
4. Compare and contrast the use of anaerobic and aerobic microbes in waste treatment.
5. Define *maximum oxygen consumption*, *VO_2 max*.
6. (a) Determine the value of the lactic acid threshold from **Figure 10**.
   (b) What does this value mean?
7. When Henry Ford built the first Model T in 1908, he expected it to run on pure ethanol produced by fermenting corn. From 1920 to 1924, the Standard Oil Company in Baltimore produced and sold a mixture of ethanol and gasoline called gasohol. However, high corn prices and transportation difficulties terminated the project.
   (a) Research gasohol on the Internet or at the library. List three advantages and three disadvantages of gasohol production in Canada.
   (b) Comment on the viability of a gasohol industry in Canada.

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8. Alcoholic beverages, such as wine and beer, have been produced by humans since the earliest days of agriculture. How do you suppose the process of fermentation was first discovered?

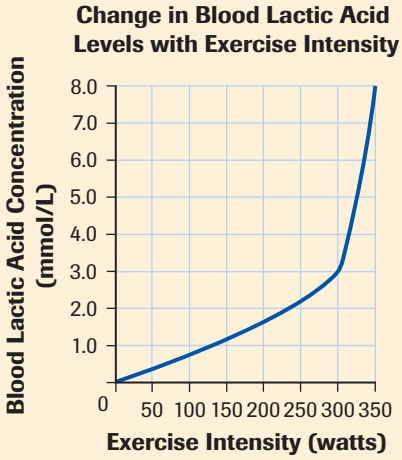

Figure 10

9. Lactic acid fermentation is used in the food industry. Use Internet and print sources to answer the following questions.
   (a) What foods depend on lactic acid fermentation?
   (b) What microbes are used in each food in (a).

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10. Conduct library and/or Internet research to answer the following questions.
   (a) How do long-distance runners make use of the lactic acid threshold in their training?
   (b) What is blood doping? What are the perceived metabolic benefits of this practice? What are some of the dangers associated with blood doping?

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11. Investigate the claim that, historically, Aboriginal athletes were some of the world's greatest long-distance runners.

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INVESTIGATION 7.1

Measuring Oxygen Consumption in Germinating Seeds

When seeds are dormant, they are not actively growing. When the right conditions are met, a dormant seed germinates and begins to grow into a seedling. As growth occurs, cells release the energy stored in cellular compounds such as starch and glucose by breaking them down. The cells then use this energy to fuel their growth. When oxygen is present, energy is released through the process of cellular respiration. The following equation summarizes this process:

$$C_6H_{12}O_6(s) + 6\,O_2(g) \rightarrow 6\,CO_2(g) + 6\,H_2O(l) + \text{energy}$$

$$\text{glucose} + \text{oxygen} \rightarrow \text{carbon dioxide} + \text{water} + \text{energy}$$

The higher its energy demands, the more quickly a cell will consume both glucose and oxygen. In this investigation, you will compare the energy demands of dormant (dry) seeds and germinating (pre-soaked) seeds by measuring the rates of oxygen consumption using an apparatus called a respirometer.

The respirometer you will use consists of a test tube with a three-hole stopper that holds a thermometer and a straight and a bent piece of glass tubing. When assembly is complete, the respirometer is sealed off from the outside air. The sealed respirometer also contains solid potassium hydroxide (KOH) pellets. KOH reacts with carbon dioxide gas according to the following chemical equation:

$$CO_2(g) + 2\,KOH(s) \rightarrow K_2CO_3(s) + H_2O(l)$$

$$\text{carbon dioxide} + \text{potassium hydroxide} \rightarrow \text{potassium carbonate} + \text{water}$$

This reaction with carbon dioxide gas produces a solid (K_2CO_3) and a liquid (H_2O). Therefore, any carbon dioxide gas produced during respiration will not contribute to the volume of gas in the respirometer.

Any change in the volume of gas inside the respirometer will cause the food colouring to move within the bent glass tubing. If gases are consumed, the food colouring will move toward the test tube. The rate of oxygen consumption can be determined by measuring the distance the food colouring moves over time.

The thermometer can be used to determine whether or not actively germinating seeds absorb or release thermal energy.

Report Checklist

○ Purpose	○ Design	● Analysis
○ Problem	○ Materials	● Evaluation
○ Hypothesis	○ Procedure	● Synthesis
● Prediction	● Evidence	

Problems

How does the rate of oxygen consumption by germinating and nongerminating pea seeds vary? Do the activities of germinating seeds absorb or release thermal energy?

Predictions

(a) Predict whether germinating or non-germinating pea seeds will consume more oxygen in 15 min.

(b) Predict whether germinating and/or or non-germinating pea seeds will absorb or release thermal energy

pea seeds (dry and pre-soaked)
water
paper towels
nonabsorbent cotton
laboratory scoop or forceps
potassium hydroxide pellets (KOH)
petroleum jelly
liquid food colouring
tape
safety goggles
laboratory apron
2 thermometers
2 straight glass tubes
2 bent glass tubes
2 three-hole test-tube stoppers
2 large test tubes
2 millimetre rulers
2 pinch clamps
2 pieces of rubber tubing
2 test-tube clamps
2 retort stands
medicine dropper

Materials

KOH is highly corrosive.

Avoid any contact with your skin. Wash under cold, running water for 5 min if you get KOH on your skin.

KOH could cause blindness. If KOH comes in contact with your eyes, wash with water for 15 min and seek medical help immediately.

Wear eye protection and a laboratory apron at all times.

Procedure

1. Place 30 dry pea seeds in a large test tube and place a layer of cotton on top of the seeds. Using forceps or a scoop, add approximately 30 KOH pellets on top of the cotton.

INVESTIGATION 7.1 *continued*

2. Assemble the respirometer as shown in **Figure 1**. Attach a millimetre ruler to the end of the bent glass tubing, using tape. Seal all stopper openings with petroleum jelly. Do not add the food colouring or the pinch clamp at this time.

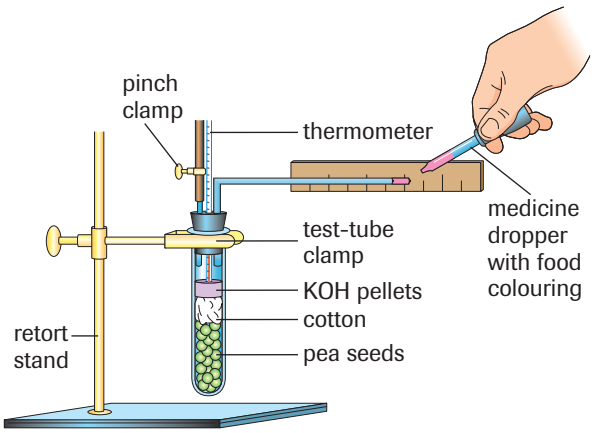

Figure 1
A respirometer

3. Repeat steps 1 and 2 with 30 pre-soaked, germinating pea seeds.
4. Allow both respirometers to stand undisturbed for 5 min.
5. With the medicine dropper, add a few drops of food colouring to the ends of the bent glass tubing.
6. Attach and close a pinch clamp to the rubber tubing on each respirometer.

(c) Record the time at which the pinch clamps were closed. Note the position of the food colouring.

(d) Measure and record the initial temperature in both respirometers.

(e) Record the position of the food colouring and the temperature inside the respirometers every minute for 15 minutes.

Analysis

(f) Graph your data by plotting the distance the food colouring moved on the *y*-axis and the time on the *x*-axis. Plot the data set for both the dry and the pre-soaked peas on the same graph.

(g) Determine the oxygen consumption rates for dry and germinating seeds using the following formula:

$$\text{average } O_2 \text{ consumption rate} = \frac{\text{total distance travelled}}{\text{total time}}$$

(h) Create a graph of temperature versus time. Plot the data for the dry and pre-soaked pea seeds on the same graph.

Evaluation

(i) Evaluate your predictions based on your analysis.

(j) Write hypotheses that explain your findings, referring to the chemical reaction for respiration.

(k) In which direction does the food colouring first move?

(l) What is the purpose of the ruler?

(m) Why was the cotton used?

(n) Explain how the respirometer works.

(o) Why were the openings in the test-tube stopper sealed with petroleum jelly?

(p) What process in the peas caused the food colouring to move into the glass tubing?

(q) How would the results of this experiment differ if KOH had not been added to the test tubes?

(r) What plant process produces oxygen gas? Explain why this process does not affect the results of this experiment.

(s) During respiration, glucose ($C_6H_{12}O_6$) is consumed. What was the source of glucose in the germinating seeds?

(t) Do actively respiring seeds absorb or release thermal energy? Account for this observation based on your understanding of the chemical reactions that occur *during* respiration.

Synthesis

(u) Seeds will not germinate if they are too wet. Why?

(v) Design and conduct an experiment to investigate the effect of temperature on the respiration rate in germinating peas. Be sure to control for the effects of temperature on the volume of gases.

Chapter 7 SUMMARY

Outcomes

Knowledge

- explain, in general terms, how carbohydrates are oxidized by glycolysis and the Krebs cycle to produce reducing power in NADH and $FADH_2$, and chemical potential in ATP, describing where in the cell those processes occur (7.2, 7.3)
- explain, in general terms, how chemiosmosis converts the reducing power of NADH and $FADH_2$ to the chemical potential of ATP, describing where in the mitochondria the process occurs (7.3)
- distinguish, in general terms, among aerobic respiration, anaerobic respiration, and fermentation (7.3, 7.4)
- summarize and explain the role of ATP in cell metabolism (7.1, 7.2, 7.3, 7.4)

STS

- explain that science and technology are developed to meet societal needs and expand human capability (7.4)
- explain that science and technology have consequences for humans and the environment (7.4)

Skills

- ask questions and plan investigations (7.3, 7.4)
- conduct investigations and gather and record data and information by: using experimental methods to demonstrate, quantitatively, the oxygen consumption of germinating seeds (7.3); measuring temperature change over time of germinating and non-germinating seeds (7.3); investigating and integrating, from print and electronic sources, information on the action of metabolic toxins, such as hydrogen sulfide and cyanide, on cellular respiration (7.4)
- analyze data and apply mathematical and conceptual models (7.3, 7.4)
- work as members of a team and apply the skills and conventions of science (all)

Key Terms

7.1

NADH
NAD^+
$FADH_2$
FAD^+
active transport
sodium–potassium pump
aerobic cellular respiration
anaerobic cellular respiration

7.2

glycolysis

7.3

mitochondrion
mitochondrial matrix
intermembrane space
Krebs cycle
oxidative ATP synthesis

7.4

alcohol fermentation
lactic acid fermentation
maximum oxygen consumption, VO_2 max
lactic acid threshold

MAKE a summary

1. Draw a large, well labelled poster summarizing the four stages of cellular respiration. Have the area of the sheet represent the cytoplasm of an animal cell. Draw a very large mitochondrion covering at least one half of the area. Add coloured cartoons representing each stage of the process and place them in their respective locations. Use arrows to indicate the movement of intermediate molecules. Show the ATP yield from each stage and the overall ATP yield from the entire process.
2. Revisit your answers to the Starting Points questions at the start of the chapter. Would you answer the questions differently now? Why?

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The following components are available on the Nelson Web site. Follow the links for *Nelson Biology Alberta 20–30*.

- an interactive Self Quiz for Chapter 7
- additional Diploma Exam-style Review Questions
- Illustrated Glossary
- additional IB-related material

There is more information on the Web site wherever you see the Go icon in the chapter.

UNIT 20 C PERFORMANCE TASK

Student Aquarist

In this Performance Task, you will create an aquatic ecosystem and manipulate its biotic and abiotic factors and monitor the effects these changes have on the metabolic health of the ecosystem's plants and animals. Go to the Unit 20 C Performance Task link on the Nelson Web site to complete this task.

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Chapter 7 REVIEW

Many of these questions are in the style of the Diploma Exam. You will find guidance for writing Diploma Exams in Appendix A5. Science Directing Words used in Diploma Exams are in bold type. Exam study tips and test-taking suggestions are on the Nelson Web site.

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DO NOT WRITE IN THIS TEXTBOOK.

Part 1

Use the following information to answer questions 1 to 3.

Figure 1 is a cut-away diagram of a mitochondrian.

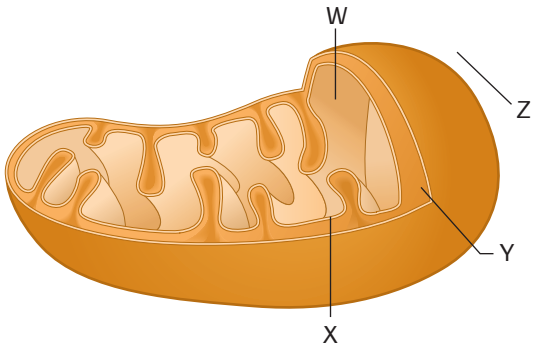

Figure 1

1. The following processes occur in the locations indicated.
   A. glycolysis (W), Krebs cycle (X), electron transport Y)
   B. glycolysis (Y), Krebs cycle (Z), electron transport (X)
   C. glycolysis (Z), Krebs cycle (W), electron transport (X)
   D. glycolysis (Z), Krebs cycle (Y), electron transport (X)

2. In an active mitochondrion the concentration of H^+ ions is greatest at
   A. W
   B. X
   C. Y
   D. Z

3. Imagine that you are able to design an experiment to measure the movement of ATP and ADP molecules within a cell. Which pattern would you expect your results to show?
   A. ATP moves from W to Y; ADP moves from Y to W
   B. ATP moves from W to Z; ADP moves from Z to W
   C. ATP moves from Y to Z; ADP moves from Z to Y
   D. ATP moves from Z to W; ADP moves from W to Z

---

4. Which of the following processes does NOT use ATP as the primary energy source?
   A. active transport
   B. muscle contraction
   C. protein synthesis
   D. osmosis

5. In glycolysis, glucose must first be activated. The activation of glucose requires
   A. two molecules of O_2
   B. two molecules of H_2O
   C. two molecules of ATP
   D. two molecules of NAD

6. Which of the following is involved in the lactic acid fermentation pathway after glycolysis?
   A. production of carbon dioxide
   B. oxidation of NADH
   C. production of ATP
   D. consumption of lactic acid

7. An increased level of aerobic fitness is associated with
   A. a low VO_2 max
   B. a high VO_2 max
   C. a low lactic acid threshold
   D. a high VO_2 max and a low lactic acid threshold

8. NR Each of the following compounds can be used by a cell to produce ATPs. Choose the four compounds that could yield the greatest number of ATPs and place them in order from greatest to least energy. (Record all four digits of your answer.)
   1. pyruvate
   2. NAD^+
   3. $FADH_2$
   4. glucose
   5. NADH
   6. acetyl-CoA
   7. FAD
   8. ADP + P_i

9. NR The complete oxidation of glucose to carbon dioxide and water releases 2870 kJ of energy per mole. Aerobic respiration only captures about 930 kJ of this available energy. Calculate the approximate efficiency of aerobic respiration as a percentage to one decimal place. (Record all four digits of your answer.)

Part 2

10. **Explain** what happens to the rest of the energy in question 9.

11. (a) **Determine** the net gain in ATP when one glucose molecule undergoes aerobic cellular respiration.
    (b) **Determine** the net gain in ATP when one glucose molecule undergoes alcohol fermentation.

12. Name the four stages of aerobic cellular respiration and **describe** where in a cell each stage occurs.

13. Oxygen is the final electron acceptor in the electron transport chain. If it is only needed in the last reaction of this pathway, **explain** how a lack of oxygen causes both the electron transport chain and the Krebs cycle to come to a complete stop.

14. Oxygen is toxic or unavailable to some cells such as yeast. **Summarize** how yeast cells produce ATP from glucose.

Use the following information to answer questions 15 and 16.

Marathon runners have learned that taking walking breaks during a race may get them to the finish line faster than running all the way.

15. **Identify** the compound that is more likely to accumulate if DE the runner does not take any breaks.

16. **How** would the walking breaks influence the accumulation DE of this substance?

17. **Explain** why it is essential that muscle cells convert pyruvate into lactic acid during strenuous exercise, even though the cell obtains very little energy in this process and lactic acid accumulation causes muscle fatigue and pain.

Use the following information to answer questions 18 and 19.

A geneticist gives you two test tubes containing two types of yeast cells that are the same in every way except that one can carry out only aerobic respiration and the other can carry out only anaerobic respiration. The tubes are labelled A and B and they look the same. Yeast from tube A grows rapidly whereas yeast from tube B grows slowly.

18. **Identify** the tube that contains the cells that only perform DE aerobic respiration. **Explain** how you made your choice.

19. **Design** two different experiments that could be used to DE verify your results.

20. DE There is growing interest in the industrial production of ethanol. Sometimes referred to as "green gasoline," ethanol is used as a fuel additive for automobiles. Ethanol use is being encouraged both to reduce dependence on fossil fuels and as a way to reduce greenhouse-gas emissions. While ethanol fuel has promise, many feel that its potential is being over-stated. Use the Internet and other resources to find out more about ethanol fuel. Based on your research, write a unified response addressing the following aspects of the use of ethanol as "green gasoline."

- **Outline** the basic steps in commercial ethanol production. What sources of biomass are available to produce the ethanol and how are these materials processed to produce ethanol?
- **Explain** the potential advantages of replacing petroleum-based fuels with ethanol.
- **Summarize** the energy inputs involved in growing, transporting, and processing these biomass sources. **Explain** how these inputs influence your answer to the previous question.
- **Describe** how scientists are using genetic engineering to improve the efficiency of ethanol production.
- Brazil produces enough ethanol to meet 40 % of its primary energy needs. Does Canada have the same potential for ethanol production? Provide data to **justify** your answer.

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Extension

Use the following information to answer questions 21 to 25.

A 30-year-old, 75 kg male runner completes a marathon in 2 h and 35 min. His oxygen consumption at 15 min intervals is shown in **Table 1**. Oxygen consumption is given by the equation

$$\text{oxygen consumption (mL/min)} = VO_2 \text{ max (mL/kg/min)} \times \text{mass (kg)}$$

Table 1 VO_2 Max Data for Male Runner

Time (min)	VO_2 max (mL/kg/min)	Time (min)	VO_2 max (mL/kg/min)
0	15	150	65
15	40	165	50
30	70	180	45
45	90	195	40
60	90	210	35
75	75	225	30
90	70	240	25
105	65	255	20
120	65	270	15
135	65	290	15

21. **Sketch** a graph to display the data in **Table 1**. DE

22. **Identify** the runner's resting VO_2 max. DE

23. **Determine** his oxygen consumption while resting and DE during his highest VO_2 max.

24. **Explain** what is happening during each phase of the DE graph.

25. DE Use your knowledge of oxygen consumption during exercise to **explain** the oxygen consumption after the race is finished.

Many of these questions are in the style of the Diploma Exam. You will find guidance for writing Diploma Exams in Appendix A5. Science Directing Words used in Diploma Exams are in bold type. Exam study tips and test-taking suggestions are on the Nelson Web site.

www.science.nelson.com GO

DO NOT WRITE IN THIS TEXTBOOK.

Part 1

Use the following information to answer questions 1 to 3.

The three graphs in **Figure 1** represent energy profiles of chemical processes that occur within cells.

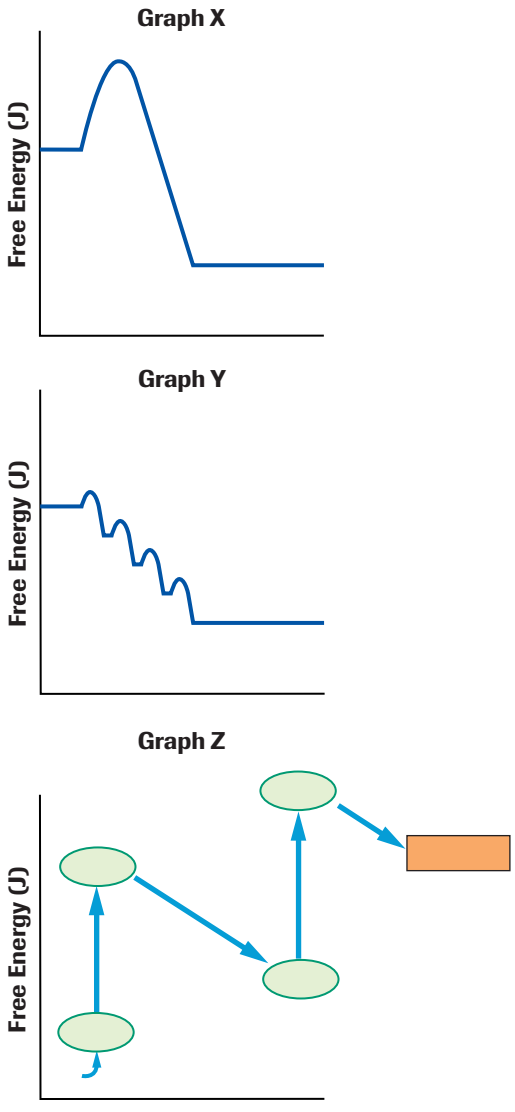

Figure 1

1. The three energy profiles could represent the following processes:
   A. a single reaction (X); the light-dependent reactions (Y); the Krebs cycle (Z)
   B. the electron transport chain (X); glycolysis (Y); the light-dependent reactions (Z)
   C. the Krebs cycle (X); the electron transport chain (Y); glycolysis (Z)
   D. a single reaction (X); the electron transport chain (Y); the light-dependent reactions (Z)

2. The jumps in the energy profile in Graph Z represent
   A. the addition of ATP energy
   B. redox reactions
   C. the absorption of light energy
   D. the action of enzymes

3. In Graph X, the initial increase in energy represents
   A. the energy needed to break bonds
   B. the energy released as bonds form
   C. the energy provided by ATP
   D. an energy increase due to the addition of an enzyme

4. The range of wavelengths of light that is visible to humans is
   A. 380 nm – 550 nm
   B. 400 nm – 600 nm
   C. 380 nm – 750 nm
   D. 200 nm – 900 nm

Use the following information to answer questions 5 and 6.

Figure 2 shows major steps in photosynthesis and cellular respiration, and the molecules that link these two processes.

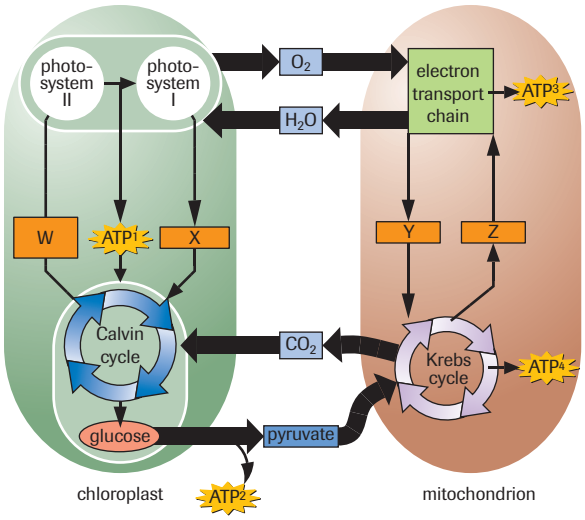

Figure 2

5. Labels W, X, Y, and Z correspond to
   A. H_2O (W); O_2 (X); pyruvate (Y); CO_2 (Z)
   B. O_2 (W); H_2O (X); CO_2 (Y); pyruvate (Z)
   C. O_2 (W); H_2O (X); pyruvate (Y); CO_2 (Z)
   D. CO_2 (W); pyruvate (X); O_2 (Y); H_2O (Z)

6. The ATPs that are of value to the cell for performing cellular functions such as active transport and movement are
   A. all the ATPs
   B. ATP 1 and 2 only
   C. ATP 3 and 4 only
   D. ATP 2, 3, and 4 only

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7. NR Choose the steps from the following list that occur in photosynthesis and place them in the order in which they occur in the cell. (Record all four digits of your answer.)
   1. NAD^+ is reduced
   2. H_2O is split
   3. acetyl-CoA forms
   4. CO_2 is produced
   5. CO_2 is fixed
   6. NADPH is oxidized
   7. $FADH_2$ is oxidized
   8. ATP is used

8. NR Using the following formula, calculate the VO_2 max for a 29 year old male with a mass of 80 kg who is able to walk 1.6 km in 8.5 minutes with a final heart rate of 78 beats per minute. (Record your answer to one decimal place.)

VO_2 max (mL/kg/min) =
$132.853 - 0.1696m - 0.3877a + 6.3150g - 3.2649t - 0.1565r$

Part 2

9. **Summarize** what happens during the light-dependent reactions of photosynthesis.

10. **Compare** the general equations of photosynthesis and aerobic respiration. **Outline** the similarities and differences in a table.

Use the following information to answer questions 11 to 13.

Hibernating animals rely on a special kind of tissue called brown fat. This tissue is located around vital internal organs, such as the heart, liver, and kidneys, and releases an unusually large amount of thermal energy when it is metabolically active. This occurs when the animal is "waking up" from hibernation. Researchers have discovered that the mitochondria in this tissue produce a chemical that disrupts the functioning of the electron transport chain, by making the inner membrane permeable to H^+ ions. A drug, dinitrophenol, has the same effect on mitochondria in normal tissues. The drug was prescribed in low doses the 1940s to help obese patients lose weight but its use was discontinued after several patients died.

11. DE **Explain** whether the mitochondria in brown tissue would be able to generate more ATP than the mitochondria in normal tissue.

12. DE **How** would the permeability of the inner membrane to H^+ ions result in additional thermal energy production?

13. DE **Hypothesize** how using dinitrophenol could have caused the deaths.

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14. (a) In active muscle tissue, **explain** what happens when the supply of oxygen is not adequate for the demands of oxidative phosphorylation.
    (b) **Why** does deep breathing continue even after strenuous exercise (e.g., running) has stopped?

15. Chemical bonds are forces of attraction that exist between atoms. These forces of attraction vary in their strength. When a chemical reaction occurs, old bonds break and new bonds form as atoms become rearranged. Use this information to **explain** how some reactions require energy while others release energy.

Use the following information to answer questions 16 to 22.

Many people are aware that plants produce oxygen gas—a gas that we need to breathe. This understanding has led to the widespread belief that entire ecosystems such as forested areas are net producers of oxygen. This belief, however, is somewhat misleading. In order for there to be a net production of oxygen gas, photosynthesis must be occurring faster than cellular respiration. The following equations summarize the overall reactions of photosynthesis and respiration:

$6\ CO_2 + 12\ H_2O + \text{solar energy} \rightarrow C_6H_{12}O_6 + 6\ H_2O + 6\ O_2$

$C_6H_{12}O_6 + 6\ O_2 + 36\ ADP + 36\ P_i \rightarrow 6\ CO_2 + 6\ H_2O + 36\ ATP$

16. DE **Identify** the chemical process that produces oxygen gas.

17. DE **Identify** the chemical process that consumes oxygen gas.

18. DE If there were a net production of oxygen gas in an ecosystem, **identify** the chemical that must be accumulating. **Identify** the atmospheric chemical that must be decreasing in concentration.

19. DE **How** would this affect the total biomass of the ecosystem over time?

20. DE **Explain** whether it is possible for such a situation to continue over a very long period of time.

21. DE **Outline** some natural processes that keep biomass from accumulating over time.

22. DE **How** might our understanding of these relationships influence strategies to combat climate change?

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23. Review the focusing questions on page 174. Using the knowledge you have gained from this unit, briefly **outline** a response to each of these questions.